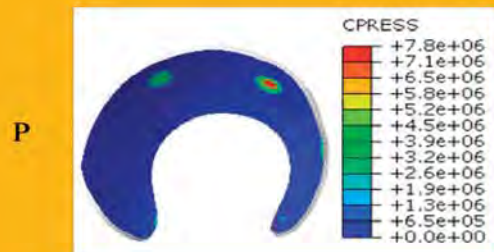
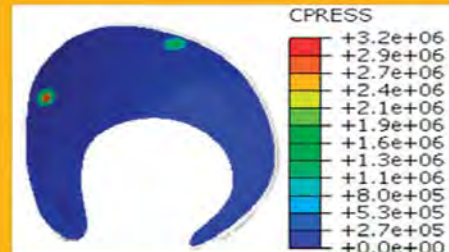


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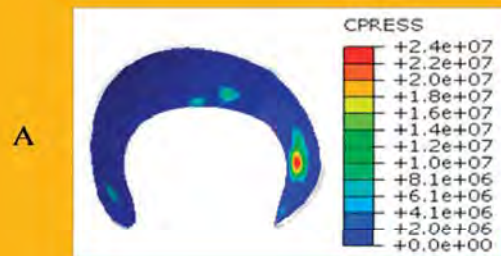
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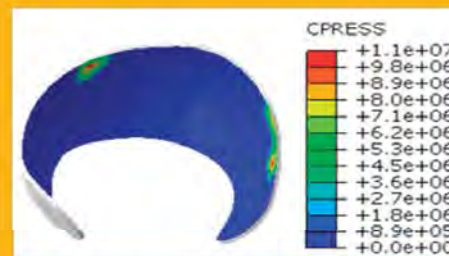
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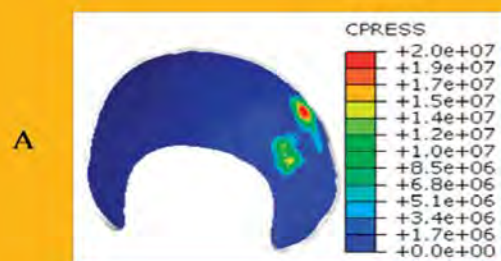
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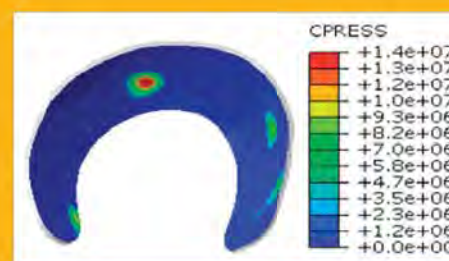
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A P2



P A



P P3

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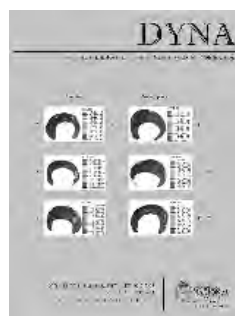
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Primer acercamiento a la mecánica de contacto en amputados transfemorales unilaterales

Autores:
Isabela Mariaka-Flórez & Juan Fernando Ramírez-Patiño



Probabilistic analysis of the active earth pressure on retaining wall for c - ϕ soil backfill under seismic loading conditions

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Abstract

This paper describes a methodology based on the Rosenblueth point estimate method to analyze the active earth pressure developed on retaining walls for c - ϕ soil backfill under seismic loading conditions. The fundamentals of this methodology are to use two point estimates to examine a variable in the safety analysis: the mean value and the standard deviation. When the horizontal seismic acceleration coefficient increases, the overturning factor of safety decreases, whereas the probability of failure increases, particularly for coefficients greater than 0.2. In addition, the mean factor of safety increases when the vertical seismic acceleration coefficient increases, but the probability of failure remains practically identical for the considered critical factor of safety (1.15).

Keywords: probabilistic analysis; point estimate method; retaining wall; seismic loading; factor of safety; probability of failure.

Análisis probabilístico del empuje activo en muros de retención con relleno cohesivo-friccionante bajo condiciones de carga sísmica

Resumen

En este artículo se describe una metodología basada en el método de estimación puntual de Rosenblueth para el análisis del empuje activo desarrollado en un muro de retención con relleno cohesivo-friccionante bajo condiciones de carga sísmica. El principio básico de esta metodología es usar dos estimaciones puntuales, *i.e.*, la desviación estándar y el valor medio, para examinar una variable en el análisis de seguridad. Es posible mostrar que aumentando el valor del coeficiente de aceleración sísmica horizontal, el factor de seguridad por volteo decrece y la probabilidad de falla aumenta, especialmente para coeficientes mayores que 0.2. Por otro lado, es observado que el valor medio del factor de seguridad crece cuando aumenta el coeficiente de aceleración sísmica vertical, sin embargo la probabilidad de falla se mantiene prácticamente igual para el valor del factor de seguridad considerado como crítico (1.15).

Palabras clave: análisis probabilístico; método de estimación puntual; muro de retención; carga sísmica; factor de seguridad; probabilidad de falla.

1. Introduction

Retaining walls are structures that are usually constructed to form roads, stabilize trenches and soil slopes, and support unstable structures. From the last century until now, works have been performed on the reliability-based design of earth retaining walls, such as [1,3,4,8,18,22-27].

Their design must satisfy two major requirements: internal stability, which is ensured by sufficient resistance against bending moments and shear forces, and external

stability, which indicates that except for small movements necessary to mobilize the earth pressures, the wall must be in equilibrium under external forces [15]. These structures are designed to withstand the lateral earth and water pressures, effects of surcharge loads, self-weight of the wall, and earthquake loads in particular cases. Four failures modes can be considered in the design of a gravity retaining wall: (1) overturning of the wall about its toe, (2) sliding along its base, (3) bearing capacity failure of the foundation soil, and (4) overall failure.

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The reliability of a geotechnical design depends on the safety factor, methods of analysis, calculation models, definition of the factor of safety, reliability of the geological model, assessment of the appropriate geotechnical parameters and construction quality. Because of these characteristics, in addition to the common factor of safety analysis, a probabilistic analysis has been used in this paper to illustrate an application of the design of retaining walls.

This paper presents a Mathematica code [21], which was developed for the Rosenblueth point estimate approach [16]. The authors successfully verified the code by computing the overturning failure probability of a retaining wall under static and seismic loading conditions. Based on these results, a design analysis was evaluated.

2. Factor of safety under seismic conditions

The existing deterministic approach evaluates the factor of safety against overturning failure about the wall's toe as follows [19,2] (Fig. 1):

$$FS = \frac{M_{resisting}}{M_{overturning}} \quad (1)$$

where $M_{resisting}$ [ML²T⁻²] is the actual resisting moment, and $M_{overturning}$ [ML²T⁻²] is the overturning moment. The actual resisting moment is given by:

$$M_{resisting} = W_1 Arm_1 + W_2 Arm_2 \quad (2)$$

with:

$$W_1 = \frac{1}{2} \gamma_{wall} bH \quad (3)$$

$$W_2 = \gamma_{wall} aH \quad (4)$$

$$Arm_1 = \frac{2}{3}b \quad (5)$$

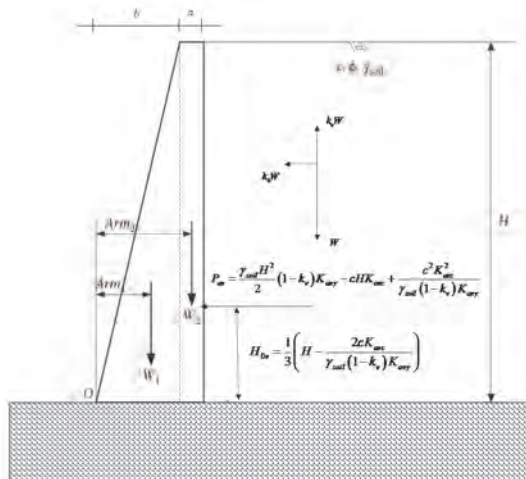


Figure 1. Geometry of the analyzed retaining wall.
Source: The authors.

$$Arm_2 = b + \frac{a}{2} \quad (6)$$

where W_1 and W_2 [MLT^{-2}] are the component weights of the retaining wall with horizontal lever distances Arm_1 and Arm_2 [L], respectively, which are measured from the toe of the wall; γ_{wall} [$\text{ML}^{-2}\text{T}^{-2}$] is the unit weight of the retaining wall concrete; $(a + b)$ [L] is the width of the base of the wall, and H [L] is the height of the wall.

Under seismic loading conditions, the overturning moments is (according to [18]):

$$M_{overturning} = P_{ae}H_{0e} \quad (7)$$

with:

$$P_{ae} = \frac{\gamma_{soil} H^2}{2} (1 - k_v) K_{ae\gamma} - c H K_{aec} + \frac{c^2 K_{aec}^2}{\gamma_{soil} (1 - k_v) K_{ae\gamma}} \quad (8)$$

$$H_{0e} = \frac{1}{3} \left[H - \frac{2cK_{aec}}{\gamma_{soil}(1 - k_p)K_{aev}} \right] \quad (9)$$

where P_{ae} [MLT⁻²] is the seismic active earth thrust with a vertical lever distance H_{0e} [L]; K_{aec} and $K_{ae\gamma}$ are the seismic active earth pressure coefficients:

$$K_{aec} = \frac{\cos \phi (1 + \tan^2 \eta_c)}{\tan \eta_c (\cos \phi + \tan \eta_c \sin \phi)} \quad (10)$$

$$K_{aey} = \frac{\cos(\phi - \psi) - \frac{\sin(\phi - \psi)}{\tan \eta_c}}{\cos \psi (\cos \phi + \tan \eta_c \sin \phi)} \quad (11)$$

with:

$$k_h = \frac{a_h}{g} \quad (12)$$

$$k_v = \frac{a_v}{g} \quad (13)$$

$$\tan \psi = \frac{k_h}{1 - k_v} \quad (14)$$

$$\begin{aligned} & \tan \eta_c \\ &= \frac{\sin \phi \sin(\phi - \psi) + m \sin 2\phi + \sqrt{f(\phi, \psi)}}{\sin \phi \cos(\phi - \psi) + 2m \cos^2 \phi} \quad (15) \end{aligned}$$

$$f(\phi, \psi) = \sin \phi \sin(\phi - \psi) \cos \psi + 4m^2 \cos^2 \phi + 2m \cos \phi [\sin \phi \cos \psi + \sin(\phi - \psi)] \quad (16)$$

$$m = \frac{c \cos \psi}{\gamma_{soil} H (1 - k_v)} \quad (17)$$

where a_h is the horizontal component of the earthquake acceleration (LT^{-2}), a_v is the vertical component of the earthquake acceleration (LT^{-2}), and g is the acceleration due to gravity (LT^{-2}).

Seismic forces that are applied to the mass of the slope are based on a horizontal seismic acceleration coefficient k_h (Table 1). The vertical seismic acceleration coefficient k_v is considered equal to zero.

The minimum factor of safety against overturning failure under seismic loading is 75% of the minimum factor of safety against overturning failure under static loading. The minimum factor of safety against overturning failure under seismic loading is 1.15 [17].

3. Deterministic approach analysis

A parametric evaluation was conducted to evaluate the factor of safety against overturning failure about the wall's toe under a seismic loading condition (Fig. 1) using the deterministic approach in Eqs. (1)-(17). Table 2 describes the parameters in this evaluation. The parameters and properties in this assessment are assumed to be estimated based on a limited number of data or expert opinion.

The first case was evaluated to describe the effect of the strength properties of the backfill in the overturning stability of the retaining wall under seismic loading conditions. Fig. 2 shows that the overturning factor of safety increases with the increase in internal friction angle of the backfill when the parameters H , a , b , γ_{wall} , γ_{soil} , c , and k_v remain constants. Fig. 2 also shows that for stability conditions ($FS_{seismic} \geq 1.15$), the value of k_h must be less than 0.3.

Table 1.
Recommended horizontal seismic coefficients.

k_h	Description
0.05 – 0.15	In the United States [13]
0.12 – 0.25	In Japan [13]
0.1	“Severe” earthquakes [20]
0.2	“Violent, destructive” earthquakes [20]
0.5	“Catastrophic” earthquakes [20]
0.1 – 0.2	FS > 1.15 [17]
0.1	Major earthquakes, FS > 1.0 [6]
0.15	Great earthquakes, FS > 1.0 [6]
½ to 1/3 of PHA	FS > 1.0 [12]
½ of PHA	FS > 1.0 [10]
0.04 – 0.11	In Mexico City [7]
0.02 – 0.86	In Mexico [5]

FS = factor of safety, PHA = peak horizontal acceleration, in g's.
Source: The authors

Table 2.
Geometry parameters and material properties

Case	Retaining Wall				Backfill			Earthquake		
	H (m)	a (m)	b (m)	γ_{wall} (kN/m ³)	γ_{soil} (kN/m ³)	c (kPa)	ϕ (°)	k_v	k_h	
1	5.5	0.4	1.4	24	18	12	18-22	0	0.1-0.5	
2	5.5-10	0.4	1.4	24	18	12	20	0	0.1-0.5	
3	5.5	0.4	1.4	18-24	18	12	20	0	0.1-0.5	

Source: The authors

The second case was evaluated to describe the effect of the geometrical parameters of the wall for the overturning stability of the retaining wall under seismic conditions. Fig. 3 shows that the overturning factor of safety decreases with the increase in height of the wall when the parameters a , b , γ_{wall} , γ_{soil} , c , ϕ and k_v remain constants. This figure shows that the k_h coefficient has more effect on the lower walls ($H < 6.5$ m) because the other walls are unstable even under static conditions.

The third case was evaluated to describe the effect of the unit weight of the concrete in the overtopping stability of the retaining wall under a seismic condition. Fig. 4 shows that the overturning factor of safety increases with the increase in unit weight of concrete in the retaining wall when the parameters H , a , b , γ_{soil} , c , ϕ and k_v remain constants. In this case, for stability conditions, the value of k_h must be less than 0.24.

4. Rosenblueth point estimate method

The probability of failure can be defined as the probability that the factor of safety can be less than 1.5 considering the adverse values of the variables in its calculation. The reliability is the complement of the probability of failure. For example, if there is a 1% probability that the factor of safety against overturning failure is less than 1.5, the reliability is 99%.

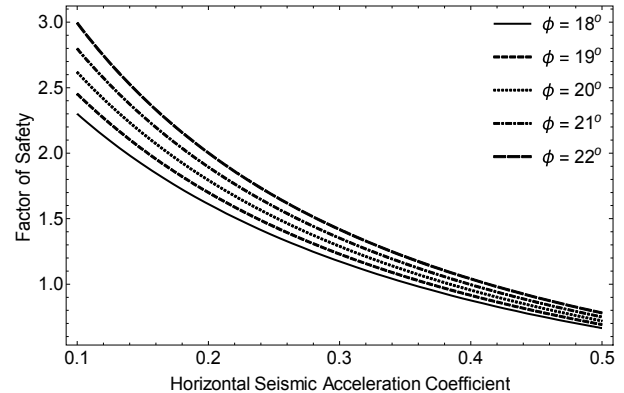


Figure 2. Effect of the strength properties of the backfill in the overturning stability of the retaining wall under seismic conditions.
Source: The authors.

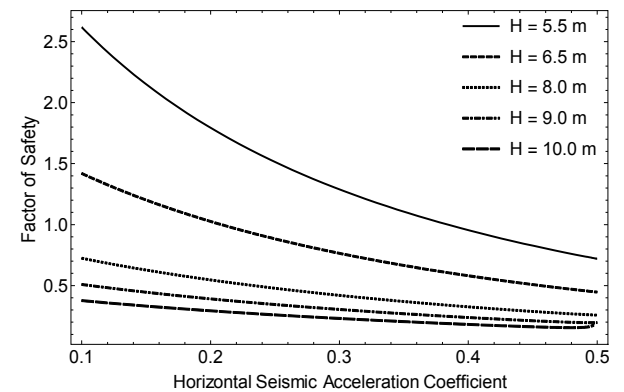


Figure 3. Effect of the geometrical parameters of the wall in its overturning stability under seismic conditions.
Source: The authors.

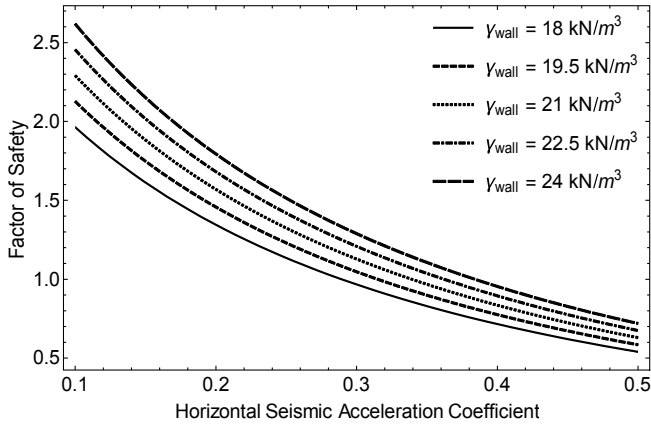


Figure 4. Effect of the unit weight of the concrete in the overturning stability of the retaining wall under seismic conditions.
Source: The authors.

The Rosenblueth point estimate method [16,8] can be used to evaluate the structural reliability of the retaining wall against overturning failure. The essence of the Rosenblueth point estimated method is to compute the mean value (μ) and standard deviation (σ) of the factor of safety (FS). This methodology selects two point estimates as $\mu \pm \sigma$ for a variable, where $\mu + \sigma$ and $\mu - \sigma$ are the positive and negative point estimates, respectively. The result is a total of 2^n combinations in point estimates if there are n variables in the governing expression of the FS . Accordingly, each combination determines 2^n FS s, from which the mean (μ_{FS}) and standard deviation (σ_{FS}) of the FS are governed by the following mathematical expressions:

$$\mu_{FS} = \sum_{i=1}^{2^n} w_i f_i \quad (18)$$

$$\sigma_{FS}^2 = \left(\sum_{i=1}^{2^n} w_i f_i^2 \right) - \mu_{FS}^2 \quad (19)$$

where f_i and w_i are the FS and weight in the i^{th} trial, respectively. The mathematical expression of w_i is:

$$w_i = \frac{1 + \sum_{j=1}^n \sum_{k=1}^n \rho_{jk} A}{2^n}, \quad j \neq k \quad (20)$$

where ρ_{jk} is the correlation (-1 to 1) between two variables. A is the determinant and equal to 1 or -1. For a given analysis, when the two variables use both positive or negative point estimates, A is equal to 1; otherwise, it is -1. Following the computations in μ_{FS} and σ_{FS} of the FS , the probability of failure can be computed.

According to the Rosenblueth approach, the factor of safety follows a normal distribution. The normal distribution of FS with μ_{FS} and σ_{FS} is described by a probability density function (PDF):

$$P_{FS}(f_i) = \frac{1}{\sigma_{FS} \sqrt{2\pi}} \exp \left[-\frac{(f_i - \mu_{FS})^2}{2\sigma_{FS}^2} \right], \quad -\infty < f_i < \infty \quad (21)$$

Since the values of the parameters of the probability density function change for each possible combination of μ_{FS} and σ_{FS} , the area under the normal distribution curve must be calculated every time the probabilities are calculated. This area is related to the distributions of any mean and standard deviation of the standard normal distribution ($\mu_{FS}=0$ and $\sigma_{FS}=1$), which is given by:

$$P(z) = \frac{1}{\sqrt{2\pi}} \exp \left[-\frac{z^2}{2} \right], \quad -\infty < z < \infty \quad (22)$$

with

$$z = \frac{f_i - \mu_{FS}}{\sigma_{FS}} \quad (23)$$

Consequently, the standard normal distribution can be integrated to calculate the area between two limits. The risk of overturning failure of a retaining wall is directly related to the probability of failure, which is obtained by integrating Eq. (24) from $z_{min}=-\infty$ to $z_{max}=\beta$:

$$\Phi(\beta) = \int_{-\infty}^{\beta} \frac{1}{\sqrt{2\pi}} \exp \left(-\frac{z^2}{2} \right) dz \quad (24)$$

β is the reliability index and corresponds to the number of standard deviations between the most likely value of the factor of safety and the minimum factor of safety against overturning, i.e.:

$$\beta = \frac{\mu_{FS} - FS_c}{\sigma_{FS}} \quad (25)$$

where FS_c is the minimum factor of safety against overturning.

The integral in Eq. (24) can be expressed in a simple closed formula:

$$\Phi(\beta) = 1 - \frac{1}{2} \operatorname{erfc} \left(-\frac{\beta}{\sqrt{2}} \right) \quad (26)$$

where $\operatorname{erfc}(x)$ is the complementary error function.

As a result, when f_i follows a normal distribution, the probability of failure (P_f) is estimated as:

$$P_f = P(FS < FS_c) = \Phi \left(\frac{FS_c - \mu_{FS}}{\sigma_{FS}} \right) \quad (27)$$

Finally, the structural reliability of the retaining wall is:

$$R = 1 - P_f \quad (28)$$

5. Probabilistic analysis

The factors that contribute to the variability of geotechnical parameters are the anisotropy and heterogeneity of the soil, soil sampling methods, and test methods. The coefficient of variation of cohesion is subject to considerable variation. In this analysis, it is 0.1–0.4. The coefficient of variation of internal friction angle is 0.02–0.13. In contrast, the coefficient of variation of unit weight is practically considered a determined value [9,11] and is 0.03–0.07.

In addition to the variability of geotechnical parameters (c , ϕ and γ), the seismic loading condition considers the variability of the horizontal seismic acceleration coefficient. The coefficient of variation of horizontal seismic acceleration, which is subject to considerable variation, is 0.26–0.34 [13].

In this analysis, the deterministic parameters H , a , b , γ_{wall} , and k_v are assumed to be constants. They are listed as follows: $H=5.5$ m, $a=0.4$ m, $b=1.4$ m, $\gamma_{\text{wall}}=24$ kN/m³ and $k_v=0$. Table 3 shows the mean, standard deviation, and coefficient of variation of the other parameters.

The governing expression of FS (Eq. 1) has four variables (c , ϕ , γ_{soil} , k_h), which results in 16 point-estimate combinations. Table 4 provides these possibilities.

The mean and standard deviation of the overturning factor of safety can be computed using Eqs. (18) and (19), respectively. Table 5 shows the calculated values considering the variables c , ϕ , γ_{soil} and k_h as independent (*i.e.*, $\rho_{jk}=0$).

Table 3.
Ranges of the backfill property variability

Property	μ	σ	COV
c	12 kPa	1.32 kPa	0.11
ϕ	20°	1.8°	0.09
γ_{soil}	18 kN/m ³	0.9 kN/m ³	0.05
k_h	0.2	0.052	0.26

Source: The authors

Table 4.
Overturning factors of safety for point estimates

i	c (kPa)	ϕ (°)	γ_{soil} (kN/m ³)	k_h	f_i
1	$\mu_c + \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	1.70
2	$\mu_c + \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	2.55
3	$\mu_c - \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	1.27
4	$\mu_c - \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	1.77
5	$\mu_c + \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	1.41
6	$\mu_c + \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	2.04
7	$\mu_c - \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	1.07
8	$\mu_c - \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma + \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	1.46
9	$\mu_c + \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	2.23
10	$\mu_c + \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	3.53
11	$\mu_c - \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	1.58
12	$\mu_c - \sigma_c$	$\mu_\phi + \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	2.27
13	$\mu_c + \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	1.82
14	$\mu_c + \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	2.75
15	$\mu_c - \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} + \sigma_{k_h}$	1.33
16	$\mu_c - \sigma_c$	$\mu_\phi - \sigma_\phi$	$\mu_\gamma - \sigma_\gamma$	$\mu_{k_h} - \sigma_{k_h}$	1.85

Source: The authors

Table 5.
Mean, standard deviation, coefficient of variation and z-value of the Factor of Safety

μ_{FS}	σ_{FS}	COV	β
1.92	0.62	0.32	1.25

Source: The authors

Table 6.
Results of the seismic analysis of different earthquake intensities

Earthquake intensity	k_h	μ_{kh}	σ_{kh}	μ_{FS}	σ_{FS}	COV	β	P_f (%)	R (%)
Very low	0.02-0.05	0.035	0.015	3.85	1.45	0.38	1.86	3.1	96, 9
Low	0.05-0.15	0.10	0.05	2.80	0.85	0.30	1.93	2.7	97, 3
Medium	0.15-0.25	0.20	0.05	1.87	0.45	0.24	1.58	6	94
High	0.25-0.35	0.30	0.15	1.34	0.34	0.26	0.57	28	72
Very high	0.35-0.45	0.40	0.25	1.03	0.36	0.35	-0.32	62	38

Source: The authors

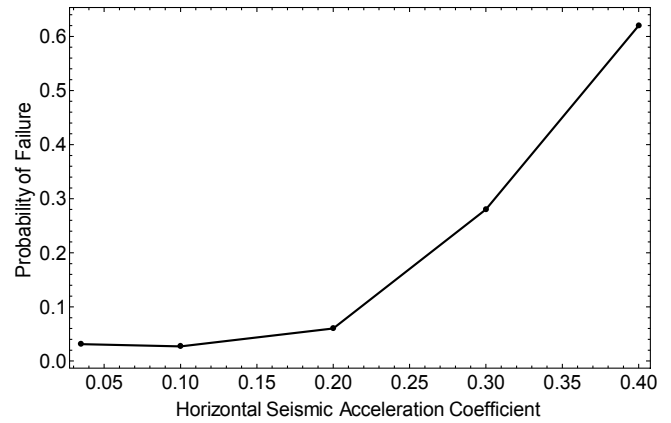


Figure 5. Probability of failure versus horizontal seismic acceleration coefficient.

Source: The authors

The probability that the value of FS is less than 1.15 is 0.11 (11%). Thus, the structural reliability of this wall against overturning failure about the wall's toe is 89%.

Thus, considering the horizontal seismic coefficients in Table 1, a seismic analysis for different earthquake intensities was conducted, as shown in Table 6.

Fig. 5 illustrates the probability of failure for different earthquake intensities. This analysis shows that when the horizontal seismic acceleration coefficient increases, the overturning factor of safety decreases, and the probability of failure increases. The probability of failure also dramatically increases from an acceleration coefficient of 0.2 (medium intensity, $P_f=6\%$) to 0.3 (high intensity, $P_f=28\%$) and 0.4 (very high intensity, $P_f=62\%$). In the interpretation of these results, it is important to clarify that this example does not consider the probability of occurrence of a certain level of seismic intensity [4].

Fig. 6 illustrates the normal distribution for μ_{FS} and σ_{FS} as described in Table 5 for different vertical seismic acceleration coefficients when the unit weight of the concrete wall is 24 kN/m³. The mean overturning factor of safety increases when the vertical seismic acceleration coefficient increases, and the critical factor of safety ($FS_c=1.15$) for the overturning analysis was reached for all values of vertical seismic acceleration coefficient. Nevertheless, for the cumulative density functions (Fig. 7), the computation of β values for each case shows that the obtained overturning probability of failure (Table 7) is practically identical for the three k_v values (8–11%).

There is some theoretical justification for the normal distribution of the factor of safety. The central limit theorem indicates that the sum of many distributions approaches to the normal distribution when the number approaches infinity. However, the use of the normal or any other theoretical distribution to form generalizations about the distributions of data is an assumption, which are made partly because they are considered reasonable approximations of reality and convenient for the calculations of probability and reliability. [14] provides a complete discussion of the use of the normal distribution.

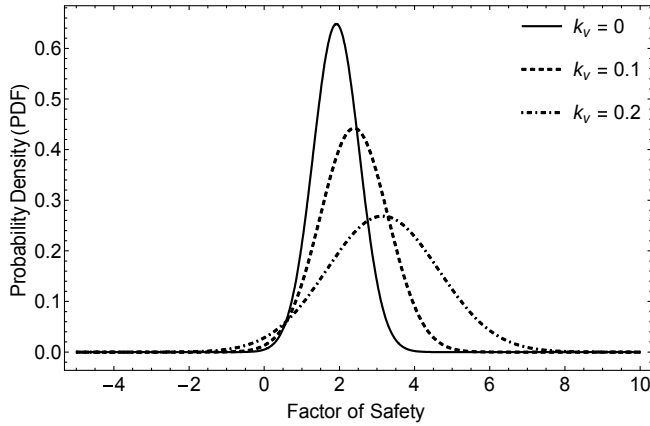


Figure 6. Normal distribution of μ_{FS} and σ_{FS} for different vertical seismic acceleration coefficients.
Source: The authors

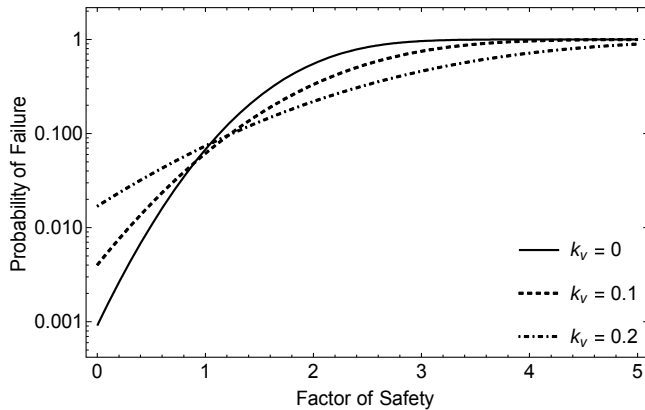


Figure 7. Probability of failure for μ_{FS} and σ_{FS} for different vertical seismic acceleration coefficients.
Source: The authors

Table 7.

Mean, standard deviation, coefficient of variation, probability of failure and structural reliability of the Factor of Safety

k_v	μ_{FS}	σ_{FS}	COV	β	P_f (%)	R (%)
0	1.92	0.62	0.32	1.25	11	89
0.1	2.39	0.90	0.38	1.37	8	92
0.2	3.15	1.48	0.47	1.35	9	91

Source: The authors

6. Conclusions

In this work, a deterministic approach is proposed to evaluate the factor of safety against the overturning failure of a retaining wall for c- ϕ soil backfill under seismic loading conditions.

A Mathematica code was implemented to compute the overturning failure probability of the wall using the deterministic approach and Rosenblueth point estimate method.

The main conclusions of the deterministic approach analysis are as follows:

- As expected, the overturning factor of safety increases with the increase in internal friction angle of the backfill, and for stability conditions ($FS_{seismic} \geq 1.15$), the horizontal seismic acceleration coefficient must be less than 0.3.
- The horizontal seismic acceleration coefficient has more effect on lower walls ($H < 6.5$ m) because the other walls are unstable even under static conditions.
- The overturning factor of safety increases with the increase in unit weight of concrete in the retaining wall. In this case, for stability conditions, the horizontal seismic acceleration coefficient must be less than 0.24.

The main conclusions of the probabilistic analysis are as follows:

- When the horizontal seismic acceleration coefficient increases, the overturning factor of safety decreases, and the probability of failure increases, particularly for coefficients greater than 0.2 (medium earthquake intensity).
- The probability of failure (not considering the probability of occurrence) dramatically increases from medium to high earthquake intensity (from 6 to 28%) and from high to very high intensity (from 28 to 62%).
- The mean factor of safety increases with the increase in vertical seismic acceleration coefficient. Nevertheless, for the considered value of the critical factor of safety (1.15), the probability of failure remains practically identical when the acceleration coefficient increases.

The paper illustrates a specific application, but the Mathematica code can be easily modified for other conditions such as when water pressures or surcharge loads are considered. The methodology in this work appears to be a good framework for designers to make decisions about the security and costs of a retaining wall project.

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los fabricantes 2 el consumidor, 1 generalmente se encuentran los centros de distribuci3n, esto debido a restricciones Sol3ticas, 53ticas o del mercado, entre otras.

Fos ti\$os de redes de distribuci3n 3or los Aue \$uede o\$tar una com\$3; 33 son diversos 2 la manera en Aue se trans\$orta la mercanc3a \$uede darse v3a terrestre, mar3tima, a3rea o 53rrea.)in embar1o, un elemento com3n de las redes de distribuci3n terrestre es el a\$ecto del ruteo, Aue considera la manera a\$ro\$3ada de distribuir la mercanc3a a trav3s de la cantidad de niveles Aue ha2a en un determinado sistema.

Fa investi1aci3n de redes de distribuci3n escalonada ha sido abordada recientemente 2 tiene 1ran a\$licabilidad en I<reas como el servicio de entre1a e3press, distribuci3n de \$productos comestibles e hi\$ermercados, comercio electr3nico 2 servicios de entre1a a casa, distribuci3n de \$rensa, 2 lo13stica en la ciudadJ G H siendo de alto inter9s el ruteo de este ti\$3o de redes el cual con un a\$ro\$3ado \$lanteamiento, \$ermite me3orar la calidad de vida de las \$ersonas, 2a Aue de manera intr3seca considera a\$sectos como la disminuci3n de la contaminaci3n 2 el ruido en las ciudades.

Fos avances dentro de la ciencia de la com\$utaci3n han \$ermido descubrir distintos m3todos \$ara la soluci3n de \$problemas com\$le3os como lo son los \$problemas de ruteo, dentro de los cuales se encuentra el !?'C6 R4 \$roblema de ruteo de veh3culos de dos escalones con ca\$acidad limitada#; estos m3todos de soluci3n a\$untan a encontrar buenas soluciones en tiem\$3os o\$ortunos, \$ermitiendo considerar nuevas 3ormas de tratarlos 2 trabajarlos a nivel te3rico.

1.2. Revisi3n de literatura

?l \$primer desarrollo 3ormal del !?'C6 R4 G Hse remonta a ! " " " *, cuando se \$resenta una formulaci3n del !?'C6 R4 basada en el 3uib3 de la mercanc3a al hacer uso de un algoritmo e3acto de rami\$icaci3n 2 acotamiento, el cual les \$ermite encontrar soluciones o\$timas a casos de hasta ! " clientes 2 dos sat3lites; adem<s en G Hse introduce la 3amilia de \$problemas de ruteo de veh3culos de dos escalones 2 se modela la versi3n b<sica de esta 3amilia de \$problemas, es decir el !?'C6 R. Fos autores \$ro\$onen un modelo de \$ro1ramaci3n lineal entera mi3ta K +F4# en el Aue las variables de decisi3n \$rinci3almente 1uardan relaci3n con el 3uib3 de car1a en cada arco; adem<s introducen desi1ualdades v<lidas \$ara el \$roblema. Tambi3n, se refieren a los algoritmos de o\$timi=aci3n a\$licados al \$roblema como heur3sticas basadas en matem<ticas las cuales combinan elementos de \$ro1ramaci3n matem<tica con metaheur3sticas; estas heur3sticas matem<ticas se basan en informaci3n recuperada de la soluci3n C\$tima de la relaci3n lineal del modelo.

?n G Hse dise; an dos heur3sticas \$ara el !?'C6 R4, Aue se enfocan en se\$3arar el \$primer escal3n del se1undo. Ambas tienen un en3oAue de dos 3ases; en la \$rimera 3ase de ambas heur3sticas se encuentra una soluci3n 3actible \$ara el ruteo del se1undo escal3n al llevar a cabo una asi1naci3n de clientes a los sat3lites; la di\$erencia es Aue una considera el \$roblema del se1undo escal3n como un con3unto de \$problemas de ruteo de veh3culos con ca\$acidad limitada C6 R4#, mientras Aue la otra lo aborda como un \$problema de

ruteo de veh3culo multi'de\$Csito K D6 R4#.

?n G Hlos autores resaltan la a\$licabilidad de sistemas de dos escalones en la lo13stica de las ciudades, la cual im\$lica la coordinaci3n de e3edidores, trans\$ortistas 2 movimientos, as3como la consolidaci3n de la car1a Aue se destinar<a los clientes en veh3culos ami1ables con el medio ambiente. ?l \$roblema Aue abordan es el !?'C6 R4 con de\$endencia de tiem\$3o, sincroni=aci3n, multi'de\$Csito, multi'\$producto, 3otas hetero19neas en cada escal3n 2 ventanas de tiem\$3o.

?n G Hse \$resenta una 3amilia de heur3sticas multi'ini3cio, las cuales se basan en se\$3arar la trans\$erencia entre. el de\$Csito al sat3lite, de la entre1a del sat3lite al cliente al resolver iterativamente estos dos sub\$problemas mediante un algoritmo de b33aAueda local basado en el cambio de asi1naci3n del cliente al sat3lite.

?n G Hse e3onen desi1ualdades v<lidas basadas en el \$roblema del a1ente via3ero T)4#2 el C6 R4 \$ara re3or=ar el modelo basado en el 3uib3; adem<s se de\$inen desi1ualdades v<lidas basadas en la interacci3n entre el ruteo 2 las variables de activaci3n de arcos, as3como tambi3n otras desi1ualdades v<lidas considerando \$ro\$iedades de conectividad 2 \$ro\$3as de una soluci3n 3actible en \$problemas de ruteo.

?n G Hlos autores \$ro\$onen una me3ora a la notaci3n de \$problemas de locali=aci3n' ruteo, introducida \$or Fa\$orte Q H en dicha notaci3n la e3resi3n $\lambda / M_1 / \dots / M_{\lambda-1}$ re\$resenta \$problemas de locali=aci3n' ruteo multi'escalonados donde λ es el n3mero de eta\$3as o ca\$3as, 2 M_i indica el ti\$3o de recorrido entre dos eta\$3as i 2 $i + 1$.)i entre las eta\$3as i 2 $i + 1$ la ruta es dedica a un 3nico cliente via3es hacia 2 desde un 3nico nodo#, entonces $M_i = R$.)i entre las eta\$3as i 2 $i + 1$ \$ueden darse rutas multi'cliente via3es a trav3s de varios v3rtices#, entonces $M_i = T$. Asimismo, sulieren marcar con una l3nea el indicativo del ti\$3o de recorrido R o T # si decisiones de locali=aci3n tienen Aue ser tomadas en la eta\$3a i . ?n este orden de ideas el !?'C6 R4 corres3onde a un \$problema3/T/T.

?n G H el autor en\$ati=a la a\$licabilidad del !?'C6 R4 en los niveles de \$laneaci3n estrat3gica, t<ctica 2 o\$erativa; \$or lo Aue los m3todos \$ara soluci3n de este ti\$3o de \$problemas deben ser \$recisos 2 r<\$idos, 2a Aue el \$roblema \$uede necesitar ser solucionado en muchas ocasiones, como \$arte de un \$proceso de o\$timi=aci3n e3tenso. Fos resultados muestran Aue el en3oAue de dos escalones es aconse3able en ciertas circunstancias 3rente al de un solo escal3n, tal Aue el !?'6 R4 es a\$licable a situaciones como entre1as de car1a en la ciudad.

?n G Hse \$lantea un modelo de o\$timi=aci3n sim3trico con una formulaci3n K +F4 \$ara el !?'C6 R4, el cual debido a la simetr3a \$rovee l3nites in\$eriores \$oco 3avorables, \$or lo Aue los autores \$ro\$onen una formulaci3n alternativa la cual consiste en una relaci3n al !?'C6 R4 Aue elimina la simetr3a 2 los l3nites in\$eriores \$oco 3avorables tras lo cual los autores idean una \$rueba de 3actibilidad 2 un esAuema de rami\$icaci3n es\$eciali=ado \$ara obtener soluciones enteras 3actibles.

?n G Hlos autores a1re1an otros com\$onentes del costo, como costos 3i3os \$or usar los arcos, costos de o\$eraci3n 2 costos ambientales; los autores estudian el im\$acto de la

conl'estiCh de tr<fico en el costo del viaje, \$or medio de an<lisis situacionales al variarlos de tal forma. Aue el costo del viaje cambia en diferentes escenarios, \$ero es constante en cada uno de ellos.

?n G% H se e0sone una heurística de bD&Aueda local ada\$titiva 2 e0tensa AFN) # \$ara el !?'C6 R4 2 el \$roblema de locali=aciCh 2 ruteo FR4#, la idea del al1orismo AFN) es llevar a cabo iteraciones en las Aue se remueve un cliente de la soluciCh actual \$or medio de un o\$erador destructor, \$ara des\$u9s, \$or medio del uso de un o\$erador re\$erador, reinsertar al cliente en otra \$osiciCh. ?l desem\$e; o del al1orismo lo1ra me0r los resultados en G.H

?n G% H se \$resenta un modelo de \$ro1ramaciCh lineal entera #4# \$ara el !?'C6 R4, asB como la im\$lementaciCh de dos al1orismos h1bridos de rami\$icaciCh 2 acotamiento, 2 1eneraciCh de columnas; uno de los al1orismos considera rutas Aue satisfacen la condiCiCh \$rimaria, 2 el otro rela&a dicha restricciCh al \$i&ar \$recios a las rutas.

?n G% H se modela el !?'C6 R4 a trav9s de una formulaciCh #4 la cual \$ermite rela&aciones enteras 2 continuas. ?l al1orismo e0acto evaluado descom\$one el \$roblema en un con&unto limitado de KD6 R4s con restricciones laterales.

?n G% H se aborda el !?'C6 R4 con una heurística Aue combina el m9todo 3 RA) 4 \$rocedimiento de bD&Aueda vora= ada\$titivo aleatorio# con un \$rocedimiento de re' encadenamiento de tra&ectorias 4ath Relin@n1#. Al i1ual Aue en otros m9todos de soluciCh; el !?'C6 R4 se divide en dos sub\$roblemas, tras lo cual se e\$ectDan las si1uientes \$ases. \$rimero, un 3 RA) 4 1enera soluciones, se1undo, si la soluciCh no es \$actible se e\$ecuta una bD&Aueda de \$actibilidad, tercero, una bD&Aueda local Aue busca me0r la soluciCh encontrada, 2 cuarto, un re' encadenamiento de tra&ectorias.

?n G% H se estudia una heurística h1brida de dos \$ases \$ara el !?'C6 R4 la cual combina 3 RA) 4 con una bD&Aueda local variable descendente 6 ND#, este al1orismo resuelve el \$roblema de aba&o hacia arriba, \$rimero un 3 RA) 4 1enera arreglos de todos los clientes 2 los asi1na a los sat9lites hasta \$resentarse una asi1naciCh \$actible, tras lo cual al resolver el \$roblema del \$rimero escalCh se obtiene la soluciCh com\$leta a la asi1naciCh \$actible encontrada, \$osteriormente el m9todo 6 ND e0\$lora en las vecindades a\$licadas. Acorde con la literatura revisada, esta heurística h1brida 1enera me0res resultados Aue las dem<s.

?n G% H se reali=a un estudio de la literatura re\$erente a \$roblemas de ruteo de dos escalones. De manera detallada abordan el \$roblema locali=aciCh' ruteo de dos escalones !?' FR4#, el !?'6 R4, 2 el \$roblema de ruteo de camiones 2 remolAues TTR4# al de\$inir en Au9 consisten, muestran un modelo matem<tico \$ara cada uno de ellos, describen \$arte de la literatura m<s relevante 2 resumen 1ran \$arte de esta informaciCh en tablas 2 1r<ficos.

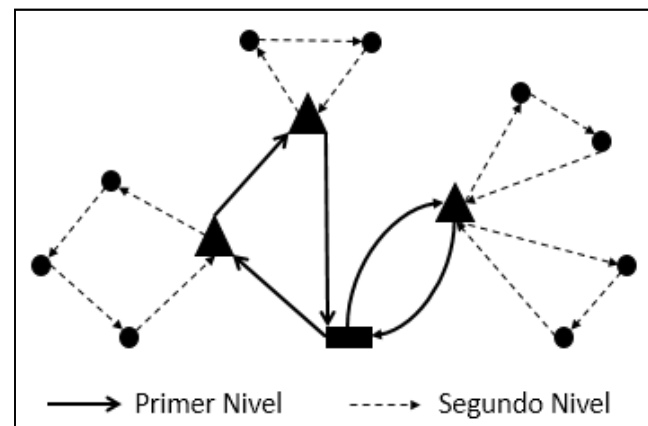
?n G% H se dise;a un al1orismo h1brido el cual aco\$la un al1orismo vora=, un al1orismo de o\$timi=aciCh basado en colonia de hormi1as AC- # 2 un al1orismo de bD&Aueda local. A \$esar de Aue el al1orismo 1enera soluciones de menor calidad com\$aradas a las soluciones de los al1orismos m<s \$recisos, 9ste tiene un me0r desem\$e; o en cuanto a la velocidad de soluciCh.

?n G% H se da a conocer su estudio del !?'C6 R4 de\$endiente del tiem\$ donde con un modelo K #4, consideran la distancia transitada, la velocidad del veh1culo, la car1a, las mDti\$les =onas de tiem\$ distintas d1as en los Aue los veh1culos via1an# 2 las emisiones. Como conclusiCh \$rinci\$al, mencionan Aue un sistema de distribuciCh de dos escalones \$rovee una soluciCh amiable con el medio ambiente, mientras Aue un sistema de distribuciCh de un Dnico escalCh entre1a soluciones de menor costo.

?n G% H se incor\$oran restricciones \$ro\$ias de la lo1stica en la ciudad, como lo son restricciones de ventanas de tiem\$, restricciones de sincroni=aciCh 2 viajes mDti\$les en el se1undo escalCh. 4ara hacer \$rente al \$roblema, los autores usan una heurística de ti\$o AFN) la cual \$ro\$orciona buenas soluciones en tiem\$os a\$ro\$ados.

2. Descripción y formulación matemática del problema

?l !?'C6 R4 consta de dos niveles o escalones, 2 el modelo matem<tico, se enfoca en solucionar el ruteo \$ara ambos de forma inte1ral, a la ve= Aue se considera minimi=ar el costo del \$roblema; se entiende como ruta de \$rimero nivel a una Aue conecta un de\$Cito central con uno o m<s centros de distribuciCh conocidos como sat9lites, 2 como ruta de se1undo nivel a una Aue conecta a un sat9lite con uno o m<s clientes Aue reAuiere una demanda, las rutas del se1undo escalCh reAuiere ser asi1nadas a al1uno de los sat9lites, mientras Aue las del \$rimero escalCh no.) e cuenta con dos \$lotas homo19neas de veh1culos, una \$ara cada nivel, siendo la \$lota del se1undo nivel menor en ca\$acidad res\$ecto a la del \$rimero nivel. Usualmente, restricciones de ca\$acidad son consideradas \$ara los sat9lites 2 veh1culos. Fa demanda de cada cliente no \$uede ser dividida en los veh1culos del se1undo nivel; sin embar1o, los veh1culos del \$rimero nivel \$ueden trans\$ortar la car1a de uno o m<s clientes, asB como servir m<s de un sat9lite en la misma ruta; cabe aclarar Aue los sat9lites \$ueden ser visitados \$or distintos veh1culos 2 las entre1as de estos \$ueden ser divididas. : inalmente, la car1a debe ser consolidada en los sat9lites \$ara su \$osterior env1o a los clientes. ?n la : i1. % se evidencia una re\$resentaciCh 1r<fica del !?'C6 R4.



: i1lura% #ustraciCh del !?'C6 R4.
: uente. Ada\$itada de G% H

De acuerdo con las especificaciones planteadas en [1] dado un grafo ponderado, completo no dirigido $G = (V, A)$ en el que el conjunto de vértices V se conforma por: un conjunto V_0 , un subconjunto V_s y un subconjunto V_c ; dichos subconjuntos con n_s satélites y n_c clientes, respectivamente.

Respecto al conjunto de aristas A , se conforma por los arcos (i, j) que representan el camino que conecta a los vértices al cual se le asocia un costo por su recorrido C_{ij} ; en el que estos costos satisfacen la desigualdad triangular en los dos escalones. A cada uno de los clientes $i \in V_c$ se le asocia una demanda d_i . Los vehículos tienen una capacidad limitada $Q_1 \leq Q_2$, para el nivel 1 y 2 respectivamente. El número total de vehículos en el primer escalón será de m^1 y para el segundo de m^2 . Además, cada satélite $k \in V_s$ tiene una capacidad B_k la cual restringe la cantidad de demanda que lleve a este desde las rutas de primer nivel. Como última limitante se tiene que m_k vehículos del primer nivel están disponibles en cada satélite $k \in V_s$.

La función objetivo del problema se expresa como la minimización de:

$$\sum_{k \in V_s} \sum_{l \in R_k} \sum_{(i,j) \in A(l)} c_{ij} x_{kl} + \sum_{r \in M} \sum_{(i,j) \in A(r)} c_{ij} y_r \quad (1)$$

En la que se busca minimizar los costos de recorrido asociados a las rutas de primer y segundo nivel.

Respecto a las restricciones se tiene que:

- Cada cliente debe ser visitado por un solo vehículo el cual efectúa una única ruta de segundo nivel.

$$\sum_{k \in V_s} \sum_{l \in R_k} x_{kl} = 1, \quad i \in V_c \quad (2)$$

- En cada satélite, el número de rutas posibles no puede ser mayor al de la cantidad de vehículos disponibles para efectuarlas.

$$\sum_{l \in R_k} x_{kl} \leq m_k, \quad k \in V_s \quad (3)$$

- El número total de rutas activas en el segundo escalón no puede exceder al número total de vehículos en este.

$$\sum_{k \in V_s} \sum_{l \in R_k} x_{kl} \leq m^2 \quad (4)$$

- La capacidad de cada satélite debe ser mayor o igual a la demanda que se consolidará en este, para su respectivo envío a los clientes.

$$\sum_{l \in R_k} \sum_{i \in R_{kl}} d_i x_{kl} \leq B_k, \quad k \in V_s \quad (5)$$

- El número total de rutas activas en el primer escalón no puede exceder al número total de vehículos en este.

$$\sum_{r \in M} y_r \leq m^1 \quad (6)$$

- La cantidad de demanda que lleve a desde las rutas de primer nivel debe ser igual a la cantidad demandada por los clientes asignados en cada satélite.

$$\sum_{r \in M_k} d_{kr} = \sum_{l \in R_k} \sum_{i \in R_{kl}} d_i x_{kl}, \quad k \in V_s \quad (7)$$

- Para cada una de las rutas posibles en las que participe un vehículo de primer nivel, la capacidad de este no puede ser excedida por la demanda de los satélites a los que sirve.

$$\sum_{r \in R_r} d_{kr} \leq Q_1 y_r, \quad r \in M, \quad (8)$$

- Las variables del modelo son de tipo binario y entero.

$$x_{kl} \in \{0,1\}, \quad k \in V_s, \quad l \in R_k \quad (9)$$

$$y_r \in \{0,1\}, \quad r \in M \quad (10)$$

$$d_{kr} \in \mathbb{Z}_+, \quad k \in R_r, \quad r \in M \quad (11)$$

3. Metodología de implementación del modelo

En la primera fase del híbrido con el que se abordará el problema se aplicará un procedimiento de búsqueda voraz adaptativa aleatoria (3RA) [4], el cual se adaptará al método en [8] dentro de esta fase se emplea un procedimiento de división (splitting procedure) basado en [4] y este procedimiento es vital para la construcción de una solución inicial en el marco de esta fase.

En la segunda fase se emplean los esfuerzos para mejorar las soluciones encontradas en la primera fase, para ello se utiliza la metaheurística de recocido simulado (SA) dentro de la cual se establecen las vecindades de búsqueda pertinentes.

3.1. Procedimiento de búsqueda voraz adaptativa

Este método iterativo consiste en generar de forma aleatoria recorridos como los del problema del agente viajero (T) [4], estos recorridos que forman parte del segundo escalón, cubren la cantidad total de clientes y son la base para aplicar el procedimiento de división, el cual permite romper el recorrido (T) en viajes asignados a cada uno de los satélites. Al conocer los clientes de cada viaje y su asignación a su respectivo satélite, es posible encontrar la demanda de cada satélite, la cual equivale a la suma de las demandas de los clientes asignados al mismo.

Con la demanda de los satélites se procede para el primer escalón a hacer tantos envíos de carga completa como sea posible desde el depósito a cada uno de los satélites, cuando la demanda remanente de cada satélite es menor a la capacidad del vehículo de primer escalón se da la condición necesaria para aplicar nuevamente el proceso de división, el cual permite dar con los viajes que servirán la demanda restante de los satélites.

3.2. Procedimiento de división

Para una determinada permutación T de clientes, se

Se procede a crear viajes a los clientes, asumiendo que un vehículo contará con capacidad infinita y se pudiera visitar a todos los clientes de acuerdo al orden establecido en esta, así como a realizar asignaciones de estos viajes a los satélites.

Este procedimiento funciona por medio de un primer auxiliar $H = (X, A, Z)$ en el que:

- X representa el conjunto de nodos desde " hasta el número de clientes.
- A simboliza el conjunto de los arcos (i, j) , $i < j$, que representan los viajes factibles, es decir los viajes que cumplan con la siguiente restricción de carga.
 - La suma de las demandas de los clientes p_{i+1} a p_j visitados en el viaje no exceda la capacidad del vehículo.

$$\forall (i, j) \in A: \sum_{i+1}^j d_{p_{i+1}} \leq Q \quad (12)$$

- Z representa el conjunto de los costos de los viajes z_{ij} de los arcos (i, j) .

A modo de ejemplo se da una permutación $= [p_3, p_5, p_1, p_2, p_4]$, donde este un vector que contiene el arreglo aleatorio de cinco clientes, se requiere además conocer la capacidad del vehículo de segundo escalón, la cual será $Q_2 = 15$, las demandas de los clientes se encuentran entre paréntesis en la : 1.1, la cual además revela los costos asumidos como distancia de ir de un nodo a otro.

Notese la posibilidad de los futuros cortes viales de ser asignados a los satélites S_2 o S_1 . El detalle del primer auxiliar H del ejemplo se evidencia en la : 1.1, .

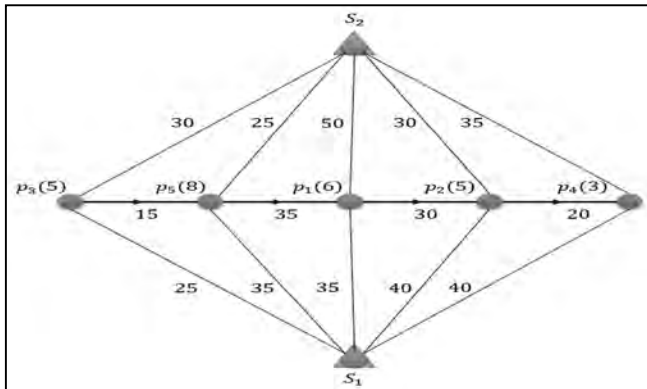


Figura 1.3. Primer auxiliar de la permutación T.
Fuente: Elaboración propia.

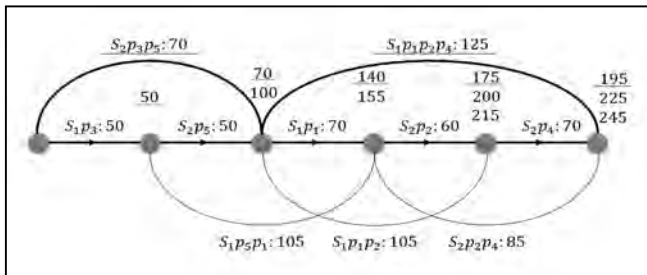


Figura 1.3. Primer auxiliar del procedimiento de división.
Fuente: Elaboración propia.

Cada uno de los arcos de la : 1.1, ., representa un viaje asignado al satélite de menor costo, para el caso del arco $p_1 p_2 p_4$ el valor del viaje desde el satélite uno sería de 100 (resultado de $100 \times 100 \times 100$), mientras que desde el satélite dos el valor sería de 100 (resultado de $100 \times 100 \times 100$), por lo cual la asignación de menor costo corresponde al satélite uno. De tal manera que el camino más corto hasta el último nodo del primer auxiliar, el cual toma un valor de 100 , indica cuál es la mejor manera de dividir la permutación, que para este caso se encuentra demarcado por los dos arcos con línea acentuada, además se evidencia como si se hubiera dividido de otra forma, los costos hubieran aumentado como en el caso de los caminos que dan un valor de 100 (resultado de $100 \times 100 \times 100$) que el resultado final del procedimiento de división aplicado al ejemplo se evidencia en la : 1.4.

3.2. Recocido simulado

La técnica de recocido simulado (H) se basa en un concepto propio de la ciencia de materiales, denominado recocido total. El H2 consiste en una solución actual s , en la que el costo asociado a esta se compara con una solución $t \in N(s)$, por lo cual la solución t pertenece a la vecindad de la solución actual s , siendo s para el caso de la primera iteración, equivalente a la primera solución obtenida de la metaheurística 3 RA 4; de tal manera que si el costo de la solución t es menor o igual al costo de la solución actual s , entonces t tomará el lugar de s ; para el caso contrario en el que el costo de la solución t sea mayor al de s , se le asigna una probabilidad a t de llegar a ser la solución actual, dicha probabilidad junto con la expresión matemática del caso se pueden expresar de la siguiente forma G&H:

$$Prob = \begin{cases} e^{-\frac{f(t)-f(s)}{tem_k}} & \text{si } f(t) - f(s) > 0 \\ 1 & \text{si } f(t) - f(s) \leq 0 \end{cases} \quad (13)$$

Donde $f(s)$ y $f(t)$ son los valores del costo asociados a las soluciones s y t respectivamente; tem_k representa la temperatura del sistema en la iteración k . Además, al analizar la expresión de probabilidad se reconoce como entre más alta sea la temperatura, mayor será la probabilidad de aceptar una solución que no mejora la actual, como la sustituta de s .

La forma clásica de representar el enfriamiento se presenta en la siguiente expresión:

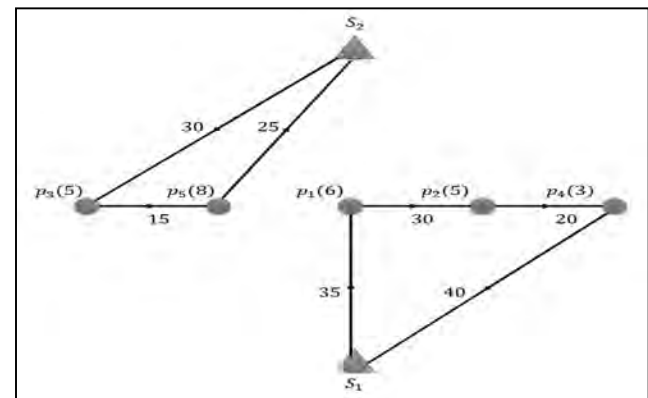


Figura 1.4. Solución por medio del procedimiento de división.
Fuente: Elaboración propia.

$$tem_{k+1} := tem_k * \beta \quad \text{donde } 0 < \beta < 1 \quad (14)$$

4or lo cual la velocidad de enfriamiento depende del parámetro β , en el que valores altos de este, significa que el sistema se enfría de una manera lenta, comparado con valores bajos de β , los cuales implican un enfriamiento más rápido.

Dado que 3 RA) 4 garantiza la exploración adecuada del problema, al incorporar el recocido simulado como ensamble de la fase de intensificación, se requiere limitar la exploración de esta, situación que se logra al mostrar por una temperatura inicial tibia G&H

En el marco de aplicación del recocido simulado, se hace vital la construcción de las vecindades G^*H sobre las cuales se lleva a cabo la intensificación de la búsqueda en el de mejorar la solución de entrada.

, !.% - \$erador de construcción !'o\$

Para una determinada ruta de segundo nivel, al usar !'o\$ se remueven dos aristas no adyacentes de la ruta, se reemplazan dos nuevas de tal forma que la dirección en la cual se atiendan los clientes dentro de los dos arcos, se da al revés G&H

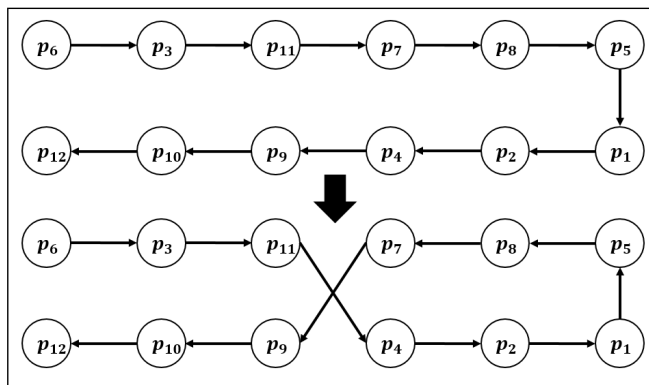
A modo de ejemplo, en la : i1. (, se evidencia como los arcos que conectan a los clientes $p_{11}, p_7 \# 2$ $p_4, p_9 \#$ son edificados; para dar lugar a los arcos $p_{11}, p_4 \# 2$ $p_7, p_9 \#$, los cuales hacen parte de la nueva ruta, en la cual además, se ve claramente como el sentido de los arcos $p_4, p_2 \#$ $p_2, p_1 \#$ $p_1, p_5 \#$ $p_5, p_8 \# 2$ $p_8, p_7 \#$ se dan en dirección contraria respecto a los arcos de la ruta no modificada.

, !.!. - \$erador de construcción - r'o\$

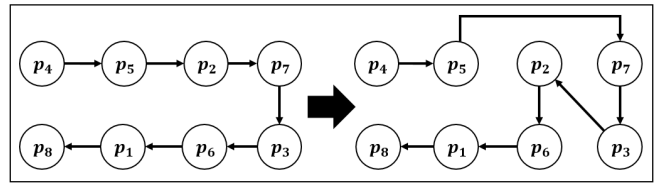
Este operador G^*H reubica la posición de un nodo cliente perteneciente a una ruta de segundo nivel, de tal forma que en el 1ro de la : i1. & se edifica como la eliminación de las aristas $p_5, p_2 \#$ $p_2, p_7 \# 2$ $p_3, p_6 \#$, las cuales forman parte de la ruta inicial; 2 la disposición de tres nuevos arcos, es decir, las aristas $p_5, p_7 \#$ $p_3, p_2 \# 2$ $p_2, p_6 \#$ dan como resultado un cambio de posición del cliente p_2 en la ruta final modificada.

, !.,. - \$erador de construcción ?o\$

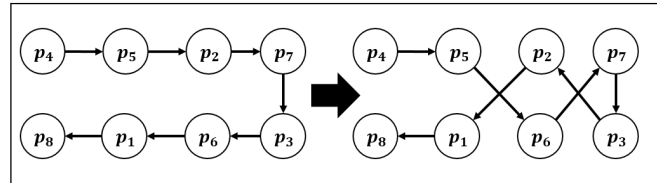
En este caso G^*H se troca la ubicación de dos nodos clientes de una ruta de segundo nivel, los cuales no tienen



: i1ura (. Aplicación del operador !'o\$.
: uente. ?laboración \$ro\$ia.



: i1ura & Aplicación del operador - r'o\$.
: uente. ?laboración \$ro\$ia.



: i1ura *. Aplicación del operador ?o\$.
: uente. ?laboración \$ro\$ia.

limitante frente a su adyacencia; por lo cual en el primer tramo de la : i1. *, al suprimir los arcos $p_5, p_2 \#$ $p_2, p_7 \#$ $p_3, p_6 \# 2$ $p_6, p_1 \#$, 2 dar cabida a los arcos $p_5, p_6 \#$ $p_6, p_7 \#$ $p_3, p_2 \# 2$ $p_2, p_1 \#$, se suscita el intercambio de los clientes p_2 y p_6 .

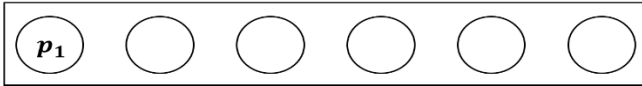
3. # (tensión del m) todo !'brido

En forma en la que funciona el procedimiento de división lleva a insertar que una permutación construida con base en criterios que consideren la distancia entre los clientes tiene una posibilidad alta de dar con soluciones iniciales de un costo bajo.

La extensión del método híbrido consiste en generar una matriz de tamaño $n \times n$, con n igual al número de clientes del problema; cada fila de la matriz corresponde a una permutación, 2 cada una de estas permutaciones debe empujar por un cliente i una única vez. A raíz de que se cuenta con las coordenadas de los clientes, se procede a calcular la distancia euclidiana entre el cliente más reciente asignado a la permutación 2 todos los demás clientes que no forman parte de esta, de tal manera que el cliente con la menor distancia se asigne en la posición $j + 1$.

Una vez se cuenta con la matriz de permutaciones, a cada una de ellas se le aplica el procedimiento de división; en el primer escalón se crea una segunda matriz de permutaciones que a diferencia de la matriz del segundo escalón, contiene todas las permutaciones posibles del conjunto de satélites, la razón por la que se generan todas las permutaciones en la matriz del primer escalón, es su factibilidad computacional en el momento de solucionar el problema, debido a la menor cantidad de satélites respecto de clientes, después se resuelve el problema para tantas permutaciones como clientes haya en el problema matriz del segundo escalón 2 cada una de estas permutaciones evaluadas con todos los ordenamientos posibles de los satélites que se solucionan por medio del procedimiento de división en el primer escalón.

A modo de ejemplo, para la construcción de la matriz de segundo escalón se considera el conjunto de clientes $C = \{p_1, p_2, p_3, p_4, p_5, p_6\}$, para el que se debe generar seis permutaciones, en la que en cada una se inicie con un cliente



: i1ura 8. Asi1naciCh inicial de la \$rimera \$ermutaciCh.
: uente. ?laboraciCh \$ro\$ia.

Tabla %
Coordenadas de los clientes.

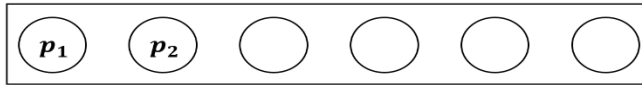
%iente	* %oor denadas	+
%	% %	! &4
!	% L	! &%
,	% "	! (4
4	% 8	! (!
(	%&	! 4*
&	%&	! 4&

: uente. ?laboraciCh \$ro\$ia.

Tabla !.
Com\$araciCh de distancias.

%ientes	Distancia
%!	8,(44
%,	!, ,!(L
%4	! (,L!
%(	! " ,8" L
%&	%&,88!

: uente. ?laboraciCh \$ro\$ia.



: i1ura L.) elunda asi1naciCh de la \$rimera \$ermutaciCh.
: uente. ?laboraciCh \$ro\$ia.

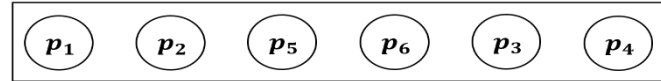
di\$erente; como se ve en la : i1. 8, la \$rimera \$ermutaciCh comien=a con p_1 , el cual se ubica en la \$osiciCh (1,1) de la matri= ver : i1. %&#.

Con los valores corres\$ondientes a las coordenadas de los clientes de la Tabla % se \$rocede a calcular la distancia euclidiana entre p_1 2 los dem=s clientes Aue aDn no se asi1nan en la \$ermutaciCh, es decir (p_2, p_3, p_4, p_5, p_6).

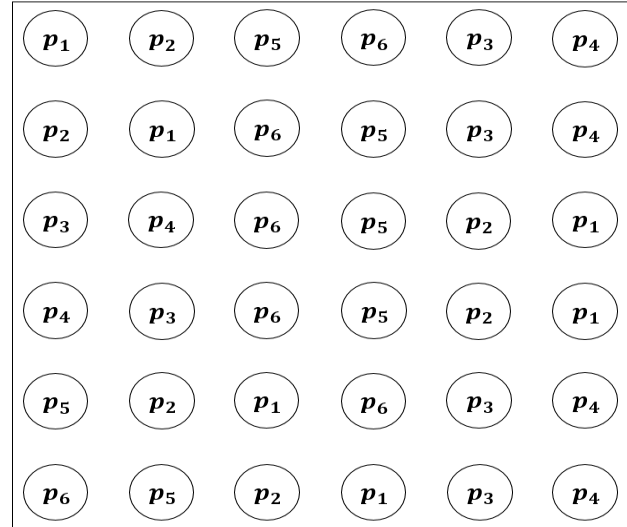
? n la Tabla !, se \$resentan los valores corres\$ondientes a la distancia entre p_1 el cliente inicial de la \$rimera \$ermutaciCh# 2 los clientes (p_2, p_3, p_4, p_5, p_6).

Como se refleja en la Tabla !, el cliente m=s cercano a p_1 es p_2 , \$uesto Aue la distancia (p_1, p_2) es i1ual a 8,(44, siendo este el escalar de menor cuantia entre las dem=s distancias, debido a ello, p_2 toma la \$osiciCh (1,2) dentro de la matri= ver : i1. %&# 2 \$or tanto la se1unda \$osiciCh de la \$rimera \$ermutaciCh como se detalla en la : i1. L.

? ste \$rocedimiento se aplica de i1ual \$orma \$ara p_2 , se resalta Aue en esta se1unda iteraciCh, no se debe considerar p_1 en la com\$araciCh de distancias con p_2 , \$uesto Aue 2a se ubicC dentro de la \$ermutaciCh en construcciCh. Al terminar las re\$eticiones de la \$rimera \$ermutaciCh se obtiene la \$rimera \$ila de la matri= la cual se muestra en la : i1. %.



: i1ura %. 4rimera \$ermutaciCh de la matri=.
: uente. ?laboraciCh \$ro\$ia.



: i1ura %%. K atri= de \$ermutaciones com\$leta.
: uente. ?laboraciCh \$ro\$ia.

Ya com\$leta la \$rimera \$ila de la matri= del se1undo escalCh, se refleja el \$rocedimiento aplicado hasta com\$letarla, teniendo \$resente Aue el \$rimer cliente de cada \$ila no debe ser i1ual en ninguna de estas, en la : i1. %& se muestra la matri= \$inal del e\$em\$lo.

: inalmente, se considera crear la se1unda matri= de \$ermutaciones res\$ecto de un determinado con\$unto de sat\$elites, sobre la cual se \$rueba cada una de las \$ermutaciones de la \$rimera matri=.

, . Resultados de la e\$perimentaci3n

4ara veri\$icar los algoritmos desarrollados, se tomaron como referencia los casos \$ro\$uestos en GH De estas se seleccionaron die= casos, las cuales se \$robaron \$or medio de los algoritmos de las t9cnicas desarrollados en KATFANO.

Tabla , .
Caracteri\$ticas de los casos.

-	l	m	n	m ₁	m ₂	K ₁	K ₂
!	&	!	!%	,	4	% " " " "	& " " "
!	&	!	, !	,	4	! " " " " "	8 " " "
!	&	!	("	,	(	4 " " "	%& "
!	,	4	("	4	(	4 " " "	%& "
,	&	!	!%	,	4	% " " " "	& " " "
,	&	!	, !	,	4	! " " " " "	8 " " "
,	&	!	("	,	(	4 " " "	%& "
4	%&	!	("	,	&	% (" " "	(" " "
4	%&	,	("	,	&	% (" " "	(" " "
4	%&	(	("	,	&	% (" " "	(" " "

: uente. Ada\$tado de GH

Tabla 4.
Resultados 3 RA) 4 vs. 3 RA) 4M) A.

Nombre	/ RA- ' 0- A	/ RA- ' 0- A	Diferencia
% ? ' n ! ! ' @ ' s % %	& (8, L	(, 8, " %	' % & , ! 8P
! . ? ' n , , ' @ ' s % L	% 4, , 4&	% 8 % *	' 4, & P
, . ? ' n (% @ ' s ! ' % %	% 4 8, (	% 1 L, 4 &	' % , 4 % P
4. ? ' n (% @ ' s ! ' 4 ' % %	% 4 ! , " (	% 8 4, 4 L	' , ! , " % P
(. ? ' n ! ! ' @ ' s % ' %	* L , (&	(L * , * * &	' ! 4, , LP
& ? ' n , , ' @ ' s % & ! !	% 4 , (8	% (" , &	' * , 8 8 P
* . ? ' n (% @ ' s % ' %	% 4 L, (	% % , &	' % , % 8 P
8. instance(" ' s ! ' " %	, % 8, " L	! * L & L L	' % , " % P
L. instance(" ' s , %	, " * 8, (L	! 8 % % , *	' 8, 8 8 P
% . instance(" ' s ' , *	, " 8 (, 4	! * L , 8 &	' L, 4 4 P

fuente: ? laboraci Ch \$ro \$ia.

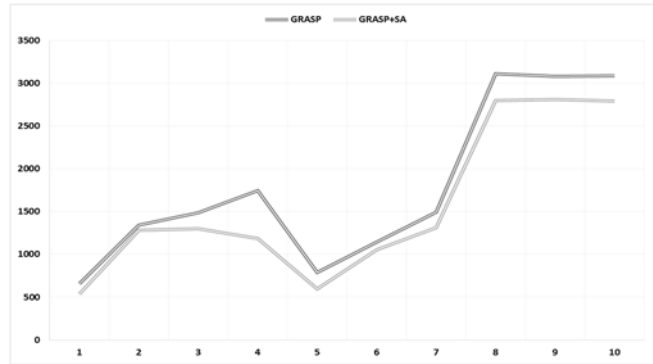


Figura 3. Comparativo 3 RA) 4 vs. 3 RA) 4M) A.
fuente: ? laboraci Ch \$ro \$ia.

En los autores elaboran un resumen de los conjuntos de casos pertenecientes al problema el cual se presenta en la Tabla 4, donde se denotan la primera columna) Conjuntos# 2 la segunda + casos#. En el caso de la primera fila, seis casos Aue forman parte del conjunto nmero dos, tienen como parámetros los valores de los costos de la fila en la Aue están presentes. En nmero de satélites se indican en la columna m, la columna n muestra el nmero de clientes, las columnas m₁ 2 m₂ representan el nmero de vehículos disponibles para el ruteo del primer 2 segundo escalón respectivamente, 2 las capacidades de los vehículos del primer 2 segundo escalón vienen dadas por K₁ 2 K₂, respectivamente.

En la Tabla 4, se presentan los resultados correspondientes al valor de la distancia costo de las soluciones correspondientes a los casos estudiados en la columna +, \$or medio del método híbrido desarrollado 3 RA) 4M) A# 2 la primera etapa de 9ste mismo método, es decir, únicamente haciendo uso de 3 RA) 4.

Respecto a la Tabla 4.

- La columna nombre indica la manera en la Aue se le llama al caso en la literatura.
- Las columnas 3 RA) 4 2 3 RA) 4M) A contienen los resultados de la aplicación de la primera parte del método híbrido 2 de la totalidad del mismo respectivamente.
- En la última columna se evidencia el porcentaje de diferencia.

De la: i1. %, se identifica como la etapa de intensificación con respecto de las soluciones iniciales arrojadas \$or 3 RA) 4

Tabla 4.
Resultados 3 RA) 4M) A vs. 3 RA) 4M) A extendido.

Nombre	/ RA- ' 0- A	/ RA- ' 0- A extendido	Diferencia
% ? ' n ! ! ' @ ' s % %	(, 8, " %	4, % (& L	' % , * 8 P
! . ? ' n , , ' @ ' s % L	% 8 % *	8 % , , " 8	' , & & P
, . ? ' n (% @ ' s ! ' % %	% 1 L, 4 &	* ! % 8 4	' 4 4, 4 (P
4. ? ' n (% @ ' s ! ' 4 ' % %	% 8 4, 4 L	* , ! , , % 4	' , 8, % 8 P
(. ? ' n ! ! ' @ ' s % ' %	(L * , * * &	(& , ! !	' (, L (P
& ? ' n , , ' @ ' s % & ! !	% (" , &	* , 8, ((&	' ! L, * % P
* . ? ' n (% @ ' s % ' %	% % , &	& * & , (4	' 4 8, 4 * P
8. instance(" ' s ! ' " %	! * L & L L	% ! (, " 8 %	' , 8, ! P
L. instance(" ' s , %	! 8 % % , *	% * , , 8 8	' , & L % P
% . instance(" ' s ' , *	! * L , 8 &	% 4 8, ! 4 *	' , * , 4, P

fuente: ? laboraci Ch \$ro \$ia.

tiene un efecto positivo en los resultados para todos los casos, de tal manera que las vecindades de búsqueda construidas a partir de los operadores ! " o\$, - r o\$ 2 ? 0chan1e, dan con soluciones mejor ordenadas en cuanto al ruteo. El efecto de la etapa de intensificación se evidencia más profundamente para el caso ? ' n (% @ ' s ! ' 4 ' % % 4& en la Aue se lleva a una variación del ' , ! , " % .

Respecto a los resultados de la Tabla 4, se considera la comparación entre 3 RA) 4 2 la ampliación de dicha técnica ver numeral , , #, en la Aue varía la forma como se generan las permutaciones iniciales previas al procedimiento de división, dejando a un lado el método aleatorio, lo cual trae efectos positivos sobre las soluciones obtenidas de dicha forma.

Respecto a la Tabla 4, las columnas abarcan el mismo significado que el de la Tabla 4, a excepción de la columna 3 RA) 4M) A extendido la cual contienen los resultados de la aplicación de la extensión del método híbrido desarrollado en el Aue se considera la técnica de construcción de las permutaciones del problema, respectivamente.

Tal como se evidencia en la Tabla 4, la extensión del híbrido permite llegar a resultados de hasta un ' 4 8, 4 * P de mejora respecto del 3 RA) 4M) A como lo es para el caso I ? ' n (% @ ' s % ' % L, lo cual demuestra como la formación de las permutaciones acorde a la extensión favorece la aplicación del procedimiento de división, puesto que la dirección en la Aue este último construye los viajes o cortes se basa en la distancia, 2 una permutación en la Aue se procuren vecinos cercanos dentro de ella permite dar con viajes más cortos. Un

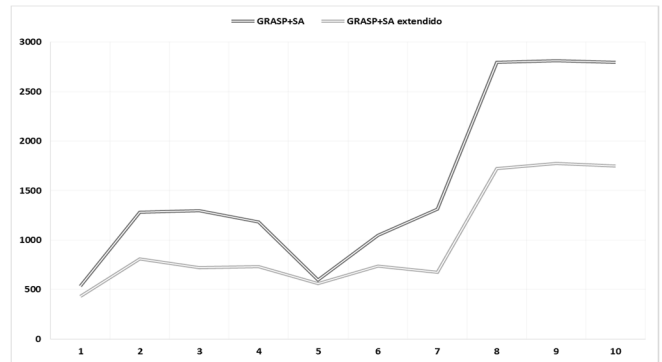
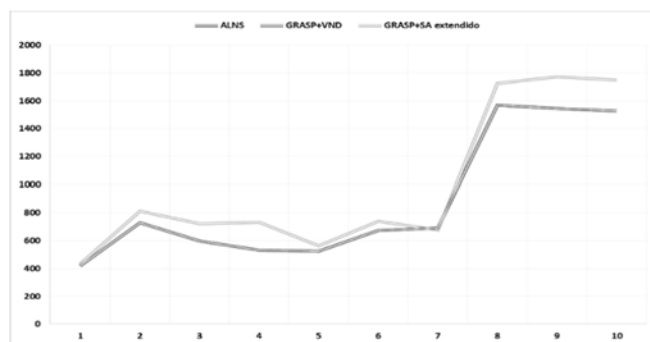


Figura 3. Comparativo 3 RA) 4M) A vs. 3 RA) 4M) A extendido.
fuente: ? laboraci Ch \$ro \$ia.

Tabla &
Resultados 3 RA) 4M6 ND vs. 3 RA) 4M) A e0tendido.

ombre	/ RA- ' 0 & D	/ RA- ' 0 - A e0tendido	Diferencia
% ? ' n ! ! ' @ ' s & %	4 % , " *	4 , % (& L	, , 48P
! . ? ' n , ' @ ' s % L	*, " , %&	8 % , , " 8	% & ! (P
, . ? ' n (% @ ' s ! ' % &	(L *, 4L	* ! % 84	! " , 8 % P
4. ? ' n (% @ ' s ! ' 4 % & 4 &	(, " , * &	*, ! , , % 4	, * , L * P
(. ? ' n ! ! ' @ ' s % ' % 4	(! & %	(& , ! !	& 88P
& ? ' n , ' @ ' s % & ! !	& * ! , %	*, 8, ((&	L, 88P
* . ? ' n (% @ ' s % ' % L	& L " (L	& * & , (4	' ! , " & P
8. nstance(" " s ! " " %	% & L, 4!	% & ! (, " 8 %	L, L! P
L. nstance(" " s , % L	% 4 & ! 8	% * , , 88 &	% 4 , * " P
% . nstance(" " s (' , *	% ! 8 , *	% & 48 , ! 4 *	% 4 , , & P

: uente. ? laboraci0n \$ro\$ia.



: i1tura %4. 3 r<ico com\$arativo 3 RA) 4M6 ND vs. 3 RA) 4M) A e0tendido.
: uente. ? laboraci0n \$ro\$ia.

\$anorama 1eneral del desem\$e; o de la e0tensi0n se muestra en la: i1. % , donde el rendimiento de esta sobre\$asa a todos los casos evaluados, con las di\$erencias \$orcentuales m<s altas en los casos Aue cuentan con los valores elevados en cuanto a la cantidad de clientes 2 sat9lites, esto se debe a Aue al aumento del dominio de soluciones del \$roblema di\$iculta la consecuci0n de \$ermutaciones aleatorias de calidad en el 3 RA) 4M) A.

4or Dltimo, se e\$ectDa la com\$araci0n entre los costos de las soluciones del m9todo 3 RA) 4M6 ND Q#H2 la t9cnica \$ro\$uesta en el \$resente trabajo, es decir, el 3 RA) 4M) A e0tendido.

Res\$ecto de la Tabla &, las columnas abarcan el mismo si1nificado Aue el de la Tabla (, a e0ce\$ci0n de la columna 3 RA) 4M6 ND donde se detallan los valores de las soluciones de Q#H

6isualmente la :i1. %4 evidencia similitud entre la e0tensi0n del 3 RA) 4M) A 2 los resultados del 3 RA) 4M6 ND, de hecho, en la Tabla & se veri\$ica como en el caso I? ' n (% @ ' s % ' % L se reduce en un ! , " &P el me0r valor encontrado hasta el momento.

1. %onclusiones

Acorde con la literatura, se evidencia una tendencia de adicionar nuevas caracter\$sticas Aue modelan situaciones de inter9s, como las relacionadas con las emisiones al ambiente, ventanas de tiem\$o, \$otas hetero19neas en cada escal0n 2 el im\$acto de la con1esti0n en los costos, entre otros. De tal

Forma Aue se \$cribe una \$ro\$ensi0n \$or modelar nuevos elementos como demandas estoc<sticas, clientes estoc<sticos, hori=ontes de \$laneaci0n de las rutas 2 env\$os al de\$Cito a trav9s de los sat9lites.

De acuerdo a la investi1aci0n, se evidencia como el !? ' C6 R4 \$uede ser con\$turado tanto a trav9s de un modelo basado en el \$u0b, asB como \$or medio de un modelo sustentado en la \$artici0n de con\$untos, siendo este Dltimo m<s com\$acto Aue el \$rimero, manteniendo todas las caracter\$sticas \$ro\$ias del \$roblema.

Res\$ecto del m9todo \$ara la soluci0n del !? ' C6 R4, se observa el \$rocedimiento de divisi0n Aue toma \$rota1onismo \$or su \$unci0n en la construcci0n de soluciones iniciales en la \$rimera eta\$a, mientras Aue, en la se1unda son los o\$eradores de construcci0n de vecindades los Aue determinan Aue se intensi\$Aue la bD\$Aueda de soluciones de ma2or calidad.

?n las \$ruebas del h\$brido inicial se re\$e\$a c0mo la intensi\$icaci0n surte un e\$ecto relevante, \$uesto Aue en la \$rimera fase ha2 un alto com\$onente aleatorio en la 1eneraci0n de las \$ermutaciones dentro de un dominio de \$osibilidades e0tenso, sin embar1o, con la \$resentaci0n de la e0tensi0n, se \$cribe Aue en la eta\$a de intensi\$icaci0n no im\$acta sustancialmente la \$unci0n ob\$etivo, debido a la calidad de las soluciones iniciales.

A \$artir de lo anterior, se \$udo evidenciar en la a\$licaci0n de las t9cnicas metaheur\$sticas Aue, el h\$brido 3 RA) 4M) A \$uncionC me0r en el % " " P de los casos Aue la t9cnica 3 RA) 4 Tabla 4#. Tambi9n Aue al incor\$orar al h\$brido las heur\$sticas de intercambio, en el % " " P de los casos diC me0res resultados Aue el anterior. Y 2a com\$arando el 3 RA) 4M) A e0tendido m9todo abordado en este art\$culo# contra la t9cnica 3 RA) 4M6 ND revisada de la literatura, se muestra en la Tabla & Aue en ! de los casos se obtienen resultados con una di\$erencia \$or encima del ! " " P , Aue en * de los casos se obtienen resultados con una di\$erencia i1n\$erior al % P . Y en uno de los casos se lo1ra me0rar la soluci0n establecida en la literatura con la t9cnica utili=ada, obteniendo una soluci0n ! , " &P me0r.

2. Recomendaciones

?n el \$resente trabajo se em\$lean o\$eradores \$ara la \$ormaci0n de vecindades, estos reali=an variaciones internas en las rutas; adem<s de este ti\$so de o\$eradores, otros se encari1an de reali=ar movimientos entre rutas como se \$uede evidenciar en la literatura, \$or lo cual se su1iere anali=ar los e\$ectos \$ositivos de una u otra clase de o\$eradores, de los cuales se evidencia como el considerar ambos ti\$os de o\$eradores \$ermita una ma2or intensi\$icaci0n en esta eta\$a.

?n el estudio de sistemas de N' escalones G %H se \$cribe la necesidad de a\$ustar el modelo del \$roblema locali=aci0n' ruteo de n' escalones al \$roblema de ruteo de veh\$culos de n' escalones con ca\$aci0n limitada G %H adem<s de crear casos \$ara \$roblemas de m<s de dos escalones.

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Procedure for Prioritisation Critical (Success Factors

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Abstract

The present article proposes a procedure to determine and prioritize the success factors in an organization by constructing a criticality index. This index is based on criticality indices to evaluate and prioritize risk, integrating the Analytical Hierarchy Process (AHP) and the fuzzy method. The procedure is applied for the prioritization of the success factors to evaluate the ethical, social responsible and sustainable behaviour, through the construction of a hierarchy that allows to classify the success factors in economic, social and environmental, in an organization oriented to the provision of customers services.

Keywords: Critical (Success Factors; analytical hierarchy process; criticality index.

Procedimiento para la Priorización de Factores Críticos de Cxito

Resumen

El conocimiento de los Factores Críticos de Cxito es fundamental en el cumplimiento de la misión y la satisfacción de las necesidades de los clientes en una organización. El presente artículo propone un procedimiento para priorizar los Factores Críticos de Cxito mediante la construcción de un índice de criticidad. Este índice tiene su base en los índices de criticidad para evaluar y priorizar riesgos, integrando el Proceso de la Jerarquía Analítica (AHP) y el método difuso. El procedimiento es aplicado para la determinación de los Factores Críticos de Cxito para evaluar el comportamiento ético, socialmente responsable y sostenible, a través de la construcción de una jerarquía que permite clasificar los Factores Críticos de Cxito en económicos, sociales y ambientales, en una organización orientada a la prestación de servicios a los clientes.

Palabras clave: Factores Críticos de Cxito; Proceso de la Jerarquía Analítica; índice de criticidad.

1. Introducción

Los Factores Críticos de Cxito han sido ampliamente utilizados desde mediados del siglo pasado en diversos temas dentro de la gestión empresarial.

Por otra parte, en los últimos años, no son pocas las inversiones desarrolladas para evaluar el comportamiento ético, socialmente responsable y sostenible de una organización.

Así, por ejemplo, desde finales de la última década del siglo pasado, numerosas instituciones y organismos internacionales han establecido normas, sistemas, índices, indicadores y herramientas que permiten conocer si la organización

se desarrolla de manera sostenible, impactando adecuadamente en la sociedad, la economía, la ecología y sobre la base de valores éticos.

Una de las ventajas de estos estándares internacionales es que presentan en su estructura temas, subtemas, dimensiones e indicadores en forma de jerarquía asociadas a factores que son claves para el éxito de una organización.

El objetivo de esta investigación es diseñar un procedimiento para priorizar los Factores Críticos de Cxito del desempeño ético, socialmente responsable y sostenible de una organización.

El procedimiento permite calcular un índice de criticidad para cada Factores Críticos de Cxito, teniendo en cuenta su impacto sobre los objetivos, su

\$robabilidad de C0ito 2 su \$osibilidad de mediciBn, asi1nando \$esos relativos a estos criterios a travGs del 3 proceso de la 6erarFu9a Anal9ica 36A# DI \$rocedimiento adem;s \$ermite evaluar la criticidad de los 5CD mediante una escala ordinal de valores.

3ara cum\$lr este objetivo los autores han estructurado esta investi1aciBn en % \$artes. 3artiendo de la introducciBn, un selundo e\$91ra4e donde se reali<a un breve resumen sobre el com\$ortamiento Gico, socialmente res\$onsable 2 sostenible de las or1ani<aciones. Dn el tercero se abordan las \$rinci\$ales caracter9sticas de los 5CD. Dn el cuarto se describen cada uno de los \$asos del \$rocedimiento \$ro\$uesto. DI Fuinto 2 se1to e\$91ra4e son dedicados a los \$rinci\$ales resultados de la a\$licaciBn de \$rocedimiento en una em\$resa de servicios in4orm; ticos 2 las conclusiones derivadas de la investi1aciBn.

2. El comportamiento ético de las organizaciones

Desde mediados del si1lo \$asado, han \$roli4erado, en el mundo de los ne1ocios, \$r; cticas e investi1aciones asociadas a la Gica em\$resarial, la res\$onsabilidad social cor\$orativa 2 la sostenibilidad de las or1ani<aciones.

Dn los 1ltimos a1os, han sur1ido nuevos conce\$tos Fue intentan inte1rar en un 1nico tGmino, el com\$ortamiento Gico, sostenible 2 res\$onsable de una or1ani<aciBn. Uno de estos es el de sostenibilidad cor\$orativa (C#.

Ha(C sere4ere a estabili<ar el desem\$e1o de la or1ani<aciBn a travGs del tiem\$o, reduciendo los im\$actos ne1ativos, econ6micos, sociales 2 ambientales, Fue se 1eneran en la obtenciBn de 1anancias 2 a\$ortando valores a lar1o \$la<o, en tGminos 4nancieros, sociales, ecol6gicos 2 Gicos 19&L.

DI conce\$to anterior est; relacionado con el desarrollo, en a1os recientes, de un 1ru\$o de instrumentos \$ara evaluar el com\$ortamiento Gico de una or1ani<aciBn, tales como normas, sistemas e indicadores, disel ados \$or or1anismos e instituciones internacionales K&%, L Dstos \$ro\$onen un 1ru\$o de dimensiones, refu\$itos, temas, subtemas e indicadores \$ara Fue las or1ani<aciones \$uedan evaluar el nivel de com\$romiso social, econ6mico 2 medioambiental 19%L.

Dstas estructuras de los est; ndares internacionales res\$onden, a lo Fue los investi1adores, han dado el nombre de modelos \$ara evaluar el com\$ortamiento Gico, socialmente res\$onsable 2 sostenible de una or1ani<aciBn. A travGs de estos se de4inen las dimensiones de los instrumentos, entre los m;s comunes se encuentran. la M3ir; mide CarrollN la M3ri\$le Cuenta de ResultadosN los Mndicadores de Desem\$e1o Ambientales, (ociales 2 de 8 obiernoN 2 los M3 3ilares de la (ostenibilidadN.

Hos 5actores Cr9ticos de C0ito del com\$ortamiento Gico, socialmente res\$onsable 2 sostenible de una or1ani<aciBn es de vital im\$ortancia \$ara el desem\$e1o de las or1ani<aciones en las com\$le4as relaciones del ; mbito econ6mico actual. A continuaciBn, los autores, resumen los \$rinci\$ales e0\$onentes, conce\$tos 2 mGodos \$ara la determinaciBn 2 \$riori<aciBn de los 5CD.

3. os! actores " r#icos de \$ %1to

DI tGmino 5actores Cr9ticos de C0ito 5CD# 4ue introducido \$or 6ohn 5. Roc@art en) =* = como un mGodo de so\$orte \$ara de4inir necesidades de in4ormaciBn en la

direcciBn de las or1ani<aciones. Anteriormente, en) =% , D. Ronald Daniel hab9a introducido el tGmino 4actores claves, \$ara enunciar los \$ocos 4actores Fue determinan el C0ito de una adecuada 1estiBn de la in4ormaciBn, lo Fue cual se considera un antecedente de los 5CD 19*L.

Hos 5CD constitu2en, un n1mero limitado de ; reas, elementos, caracter9sticas, ca\$acidades, condiciones, variables, circunstancias, actividades, acciones, tanto internas como e0ternas, Fue son esenciales \$ara Fue un individuo, de\$artamento, or1ani<aciBn, \$ro2ecto o sistema, cum\$la con su misiBn, metas u objetivos tra<ados 19 8&) L.

DI conce\$to de 5CD es mu2 utili<ado en la actualidad en di4erentes ; mbitos de las ciencias administrativas, tales como la 1estiBn de \$ro2ectos, la identi4aciBn de necesidades de in4ormaciBn de la administraciBn 2 la \$riori<aciBn de estrate1ias, la 1estiBn de \$rocesos de ne1ocios, los \$ro2ectos de desarrollo de so4t? are, la 1estiBn de la calidad, la 1estiBn de ries1os, entre otras K! & %L.

(e1I n 19 8L los 5CD tienen una naturale<a 1er; rFuica 2 se \$ueden identi4car 4 niveles. industrial, or1ani<acional, divisional e individual. Dstos autores tambi9n e0\$resan las dimensiones en las Fue se mani4estan los 5CD. interna, e0terna, monitoreo 2 ada\$titiva.

Aun Fue el mGodo ori1inal \$lantea las 4ases si1uientes. de4inir el alcance, recolectar 2 anali<ar datos, derivar 2 anali<ar los 5CD, otras investi1aciones han desarrollado mGodos \$ara identi4car 2 \$riori<ar 4actores cr9ticos. As9 \$or e1em\$lo, K *L \$lantea las 8 tGnicas \$ara identi4car los 5CD si1uientes. an; lisis ambiental, an; lisis de la estructura de la industria, o\$iniones de e0\$ertos en la industria o ne1ocio, an; lisis de la com\$etencia, an; lisis de la 4rma 19der en la industria, evaluaciBn de la em\$resa, 4actores tem\$orales e intuitivos e im\$acto del mercado sobre utilidades.

3or otra \$arte, las metodolo19as \$ara \$riori<ar los 5CD tienen su base 4undamentalmente en dos mGodos. DI \$rimero, \$ro\$uesto \$or K 8&) L se basada en la a\$licaciBn del 7 Godo Del\$hi, donde \$or rondas, un 1ru\$o de e0\$ertos asi1na valores en una escala Hi@art a los 5CD identi4cados. DI selundo mGodo \$ro\$uesto \$or K! & %L consiste en \$riori<ar los 5CD utili<ando el 3 proceso de la 6erarFu9a Anal9ica, donde a travGs de com\$araciones \$areadas, un 1ru\$o de e0\$ertos e0\$resa cuanto m; si m\$ortante es un 4actor sobre otro.

Has investi1aciones desarrolladas en los 1ltimos a1os demuestran los disimiles an; lisis 1er; rFuicos 2 dimensionales a los Fue se \$ueden asociar 5CD, \$or e1em\$lo, Robert > a\$lan 2 David 3. Norton describen 4 \$ers\$ectivas. 4nanciera, clientes, \$rocesos internos, 2 crecimiento 2 a\$rendi<a1e a las Fue asocian 5CD. A su ve< estos autores asocian indicadores a los 5CD \$ara medir el rendimiento de una or1ani<aciBn, constru2endo una 1erarFu9a Fue enla<a lo estratGico con lo o\$erativo, en una herramienta am\$liamente usada en la actualidad, el Cuadro de 7 ando +nte1ral K * & 8L.

A continuaciBn, se reali<a una descripciBn del \$rocedimiento \$ro\$uesto en este art9culo, \$ara \$riori<ar los 5CD de una or1ani<aciBn.

& ' rocedimiento para priorizar los! " E

Hos autores de la investi1aciBn \$ro\$onen un \$rocedimiento Fue combina los dos mGodos \$ara la

Se priorizan enunciados en el párrafo anterior, el 36A 2 el trabajo con expertos. A estos se le añade el diseño de un índice integral, denominado Índice de Criticidad (IC), basado en los índices de criticidad para evaluar 2 prioridades riesgos, lo que permite no solo priorizar los 5CD, sino clasificarlos según su nivel de criticidad, siendo esta la principal novedad del procedimiento propuesto (ver Fig. 1).

A continuación, se describen cada uno de los pasos que conforman el procedimiento para la priorización de los 5 Factores Críticos de Cálculo.

4.1. Definición del problema

En este paso se define el problema a resolver. Un problema es una discrepancia entre el estado actual de las cosas y el estado que se desea. Durante la definición del problema es importante partir de un diagnóstico de la situación actual, para luego determinar el objetivo de la investigación.

A partir del objetivo que se pretende desarrollar, se construye la jerarquía para determinar los 5 Factores Críticos de Cálculo más relevantes.

4.2. Construcción de la jerarquía

Hos autores de la investigación proponen para la identificación de 5 Factores Críticos de Cálculo 5CD# construir una jerarquía, lo que permite asociar los mismos, a las áreas vitales de la organización, a la problemática que se desea resolver o a la conceptualización de una temática en particular.

Estas áreas pueden denominarse temas, Sectores 2 dimensiones, 2 estarán asociadas al objetivo de la investigación. Ha. ec.)# muestra un prototipo de jerarquía para la determinación de los 5CD.

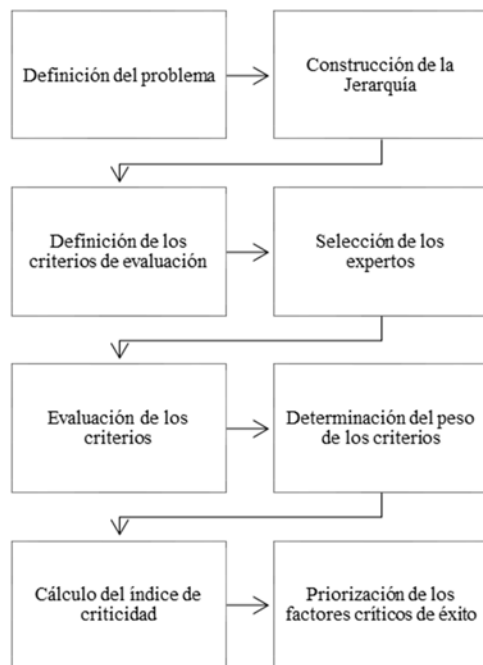


Figura 1. Procedimiento para priorizar 5 Factores Críticos de Cálculo. Fuente: Hos autores.

$$Obj = Obj(Per(FCE)) \quad)#$$

Donde.

Obj. objetivo de la investigación.

Per. Sectores.

FCE. Factores críticos de Cálculo.

Una vez construida la jerarquía es necesario definir los criterios de evaluación de los 5CD.

4.3. Definir los criterios de evaluación

Hos autores proponen evaluar los 5CD a través de tres criterios. Un primer criterio será el impacto de los 5CD sobre los objetivos de la organización, es decir, las consecuencias positivas para el cumplimiento de la misión, o de los objetivos trazados.

El segundo criterio de evaluación será su probabilidad de éxito o de fracaso. En este caso, si indica la probabilidad que tiene el 5CD de manifestarse en la organización. Es muy frecuente encontrar 5CD que tienen un impacto decisivo, pero son poco probables de que ocurran en la organización.

Por último, el tercer criterio que proponen los autores, es la posibilidad de medir los 5CD. Existen 5CD que son medibles con facilidad, pues hacen referencia a cuestiones objetivas, a su vez, existen otros que se relacionan con cuestiones más subjetivas en la organización 2 son difíciles de medir.

Hos 5CD estarán en función del impacto sobre los objetivos, la probabilidad de éxito 3e# 2 la posibilidad de medición 3m#tal 2 como muestra la ec. 1#.

$$FCE = f(Io, Pe, Pm) \quad !#$$

Una vez definidos los criterios de evaluación es necesario seleccionar los expertos que emitirán sus juicios durante la investigación.

4.4. Selección de los expertos

El trabajo con expertos es de vital importancia durante todo el procedimiento, son estos los que deberán realizar las evaluaciones de los criterios que conforman el índice de criticidad, así como también pueden ser utilizados en la determinación de los pesos asociados a los criterios.

En este paso, primeramente, se debe calcular la cantidad de expertos que intervienen en la investigación. Hos autores, utilizando un método probabilístico 2 asumiendo una ley de probabilidad binomial, proponen la ec. 1#K=L.

$$n = \frac{p * (1 - p) * k}{i^2} \quad ' \#$$

Donde.

n. Número de expertos.

i. nivel de precisión deseado.

p. Probabilidad estimada de errores de los expertos.

k. constante asociada al nivel de confianza elegido.

Huelo es necesario identificar dentro de un grupo de expertos seleccionados, aquellos que posean los

conocimientos necesarios. Los autores \$ro\$onen utilizar el m\$todo \$ro\$uesto \$or K4" & 4) L\$ara calcular el coe4iciente de com\$etencia tal 2 como muestra la ec. 4#.

$$K = 1/2(Kc + Ka) \quad 4\#$$

Donde.

K . coe4iciente de com\$etencia.

Kc . coe4iciente de conocimiento o informaci\$n.

Ka . coe4iciente de argumentaci\$n o fundamentaci\$n.

El coe4iciente de conocimiento se calcula sobre la base de un cuestionario que contiene \$re1untas de conocimientos te\$ricos 2/o \$r; cticos sobre la \$roblema; tica fue se \$retenda abordar, las \$re1untas \$ueden ser valoradas en una escala K4) L.

En el caso del coe4iciente de argumentaci\$n, este se obtiene a trav\$ de la asi1naci\$ de una serie de \$untuaciones a las distintas \$uentes de argumentaci\$ fue es1rimen los e0\$ertos K4) L. Hue1o el coe4iciente de com\$etencia es evaluado en una escala tal 2 como \$ro\$one K4) L.

4. . !valuaci\$ de los criterios

En este \$aso, los e0\$ertos anteriormente seleccionados, eval1an cada 5actor Cr4tico de C\$ito a trav\$ de su im\$acto sobre los objetivos, su \$probabilidad de \$xito 2 su \$osibilidad de medici\$n. Los autores \$ro\$onen una escala de valores ordinales, basada en escalas similares \$ro\$uestas \$or K4" & 4) L, construidas \$ara la evaluaci\$ de ries1os, a la fue se le asi1nan un 1ru\$ de eti1uetas, tal 2 como muestra la Tabla).

Al evaluar cada criterio de decisi\$ se conforma una matri\$ de decisi\$ A_{mn} donde cada elemento $a_{ij} \in A_{mn}$ 2 re\$resentan las evaluaciones emitidas \$or el e0\$erto a cada 5CD en cada criterio, donde en las 41as se ubican los 5actores Cr4ticos de C\$ito $FCE = FCE_i \forall i = 1, 2, \dots, m \neq 2$ en las columnas cada uno de los criterios evaluados $C = C_j \forall j = 1, 2, \dots, n \neq$ tal 2 como muestra la ec. , #.

$$(a_{ij})_{mn} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}, \#$$

Hue1o se \$rocede a calcular la im\$ortancia relativa \$ara cada uno de los criterios de4nidos.

Tabla).

Tabla au0iliar \$ara evaluar los criterios asociados a los 5CD

(i) el	Impacto	ogro o	* edici\$
=	D\$ce\$ional	Ase1urado	(e1uro
8	D0tremadamente	Cierto	Casi se1uro
*	7 u2 alto	7 u2 alto	7 u2 \$osible
%	Alto	Alto	3osible
,	7 oderado	7 oderado	7 oderadamente \$osible
4	3oco	Qa1o	Qa1o
'	7 enor	7 u2 ba1o	7 u2 ba1o
!	H11ero	- casional	Di4cil
)	+nsi1ni4cante	Remoto	Casi im\$osible
"	+m\$ercede\$tible	+m\$robable	+m\$osible

\$uente. Hos autores.

4.". Determinaci\$ del peso de los criterios

Para determinar la im\$ortancia relativa de los criterios, los autores \$ro\$onen utilizar el 3roceso de la 6era1ua Anal4tica 36A#, el cual fue desarrollado \$or Thomas H. (aat2 a \$rinci1ios de la d4cada de los 8".

Este asi1na un \$eso a los criterios a trav\$ de la construcci\$ de una matri\$ de com\$araci\$ \$or \$ares, donde los e0\$ertos, mediante una escala num4rica, indican cuantas veces un elemento es m; sim\$ortante fue otro K4, & 4) L.

Aun fue los autores de la investi1aci\$ su1lieren este m\$todo sub1etivo, debido a fue \$ermite evaluar la consistencia de los e0\$ertos en sus valoraciones a trav\$ del Coe4iciente de +nconsistencia CI #, e0isten otros m\$odos sub1etivos 2 objetivos fue \$ueden ser utilizados \$ara reali4ar el c; lculo de la im\$ortancia relativa de los criterios de4nidos \$ara \$riori4ar los 5CD.

4.#. C\$lculo del 4ndice de criticidad

Hos autores de la investi1aci\$ \$ro\$onen evaluar los 5actores Cr4ticos de C\$ito a trav\$ de los criterios anteriormente de4nidos inte1rados en un 4ndice de criticidad, basados en los 4ndices de criticidad e0istentes \$ara la evaluaci\$ de los ries1os o 4ndices de \$riori4aci\$ de ries1os +3R#K4" ,44,4* & " L.

Una ve4 emitidas las o\$ini\$ones de los e0\$ertos sobre cada 5CD en cada criterio, se calcula V_{ij} a trav\$ de la ec. %#.

$$V_{ij} = \frac{\sum_{i=1}^n a_{ij}}{n} \quad \% \#$$

Donde.

V_{ij} . valor \$romedio de los 1uicios emitidos \$or los e0\$ertos siem\$re fue el coe4iciente de variaci\$ en la valoraci\$ de los e0\$ertos sea menor fue ". !".

n . cantidad de e0\$ertos

Hue1o se \$rocede a normali4ar los V_{ij} a trav\$ de la ec. *#.

$$N_{ij} = \frac{V_{ij}}{VI} \quad * \#$$

N_{ij} . vector normali4ado.

VI . valor ideal de la escala de evaluaci\$ de los criterios.

El 4ndice de criticidad de los 5CD se calcular4 teniendo en cuenta la ec. 8#.

$$Ic_i = \sum_{j=1}^n N_{ij} * W_j \quad 8\#$$

Donde.

Ic_i . 4ndice de criticidad del 4actor cr4tico de C\$ito i #.

W_j . \$eso asociado a los criterios.

Hue1o se \$asar4 a \$riori4ar los 5actores Cr4ticos de C\$ito a trav\$ de la evaluaci\$ de su Ic_i .

4.% \$riori4aci\$ de los factores cr4ticos de \$xito

Al reali4ar los c; lculos con valores normali4ados se obtendr4 un 4ndice de criticidad, fue tendr4 valores entre "

Tabla 1.

Escala de valores \$ara evaluar la criticidad de los 5CD

Índice, I_{ci}	"riticidad
$0,80 \leq I_{ci} \leq 1$	7 u2 alta
$0,60 \leq I_{ci} \leq 0,79$	Alta
$0,40 \leq I_{ci} \leq 0,59$	7 edia
$0,20 \leq I_{ci} \leq 0,39$	Qaía
$0,00 \leq I_{ci} \leq 0,19$	7 u2 Qaía

5uente. Hos autores.

Tabla 1'.

5actores Críticos de C0ito asociados a la dimensi3n econ3mica.

Dimensi3n	Factores Críticos de \$ %to
Econ3mica	Reducci3n de los costos
	Defici3n del 3resu\$to
	Ahorro de los recursos
	P3ntas de servicios
	7 e\$foramiento de las condiciones de trabajo
	3nversiones en in4raestructura
	Reducci3n de los inventarios
	D0\$ortaci3n de \$rodutos
	Reducci3n de ries1os

5uente. Hos autores.

2) $0 \leq I_{ci} \leq 1$ \$ara cada 5actores Crítico de C0ito. Hos 5CD con un ma2or I_{ci} ser3n los m3s im\$ortantes \$ara la or1ani<aci3n.

Hos autores adem3s \$ro\$onen una escala \$ara clasi4car los 5CD se1In su 3ndice de criticidad I_{ci} #, tal 2 como muestra la Tabla 1'.

A continuaci3n, se muestran los resultados de la a\$licaci3n del \$rocedimiento en la \$riori<aci3n de los 5actores Críticos de C0ito del com\$ortamiento 3ico, socialmente res\$onsable 2 sostenible de una or1ani<aci3n.

/. Aplicaci3n de los resultados

Ha direcci3n de una em\$resa de \$rodutos 2 servicios in4orm3ticos en Cuba necesitaba conocer los 5actores Críticos de C0ito Fue m3s a\$ectaban su com\$ortamiento 3ico, socialmente res\$onsable 2 sostenible \$ara \$oder reali<ar una evaluaci3n de los mismos a trav3s de indicadores. Dl ob3etivo es \$riori<ar los 5CD Fue inciden en el com\$ortamiento 3ico, socialmente res\$onsable 2 sostenible de la or1ani<aci3n.

(e1uidamente se constru2B una 3erarFu3a com\$uesta \$or el ob3etivo, asociadas a este, dimensiones 2 5CD asociados a estas 3ltimas. (e el 3i3 como modelo el M3r3le Cuenta de ResultadosN \$or lo Fue se de4nen tres dimensiones. econ3mica, social 2 ambiental. Teniendo en cuenta los est3ndares internacionales Fue eval3an el com\$ortamiento 3ico, socialmente res\$onsable 2 sostenible de una or1ani<aci3n se de4nieron los 5CD \$ara las dimensiones econ3mica 2 social, tal 2 como muestran las Tablas' 2 4.

Hos 5CD de las dimensiones econ3mica 2 social identi4cados en los instrumentos internacionales, en entidades del sector de las Tecnolo3as de la 3nformaci3n 2 las Comunicaciones T+C#, no \$resentan 1randes di4erencias con res\$ecto a otros sectores de la econom3a, \$ero en el caso de la dimensi3n ambiental estas tienen caracter3sticas distintas.

Tabla 4.

5actores Críticos de C0ito asociados a la dimensi3n social.

Dimensi3n	Factores Críticos de \$ %to
Social	3rotecci3n de los derechos de los humanos
	Relaciones de trabajo
	8 arant3a de em\$leo
	(e1uridad 2 salud de los trabajadores
	5ormaci3n de los trabajadores
	3romoci3n de la diversidad 2 de la eFuidad
	Derecho 2 res\$to al consumidor
	(alud 2 se1uridad del consumidor
	Consumo res\$onsable
	3nvolucramiento con la comunidad local
Social	A\$o2o al estado 2 al 3obierno
	Com\$ortamiento anticorru\$ci3n
	Com\$ortamiento anticom\$etitivo

5uente. Hos autores.

Dn a3os recientes varias investi1aciones abordan el tema de los (istemas de 3nformaci3n Perdes, del idioma in1l3s M3reen Information -ystemsN con sus si1las 8 3 (# 2 las Tecnolo3as de la 3nformaci3n Perdes, M3reen Information . ec\$nolo yN 8 3T#.

Hos \$rimeros re4eridos al desarrollo 2 la im\$lementaci3n de sistemas de 3nformaci3n Fue contribu2an a la sostenibilidad de los \$procesos de las em\$resas; las se1undas, en4ocadas en la e4ficiencia ener13tica de los medios tecnol3gicos utili<ados \$ara la \$roducci3n de los servicios in4orm3ticos 2 su reciclaje de manera Fue no a4ecte al ambiente K) &' L.

Hos 5CD identi4cados \$ara la dimensi3n ambiental, tienen en cuenta ambos en4oFues, as9 \$or eFem\$lo la \$roducci3n ecol3tica, contiene as\$ectos tales como, el desarrollo de a\$licaciones in4orm3ticas \$ara la 1esti3n medioambiental, relacionados con los 8 3, as9 como tambi3n tiene en cuenta la cantidad de \$procesos, suministradores 2 clientes certi4cados \$or normas medioambientales, o Fue usan criterios ambientales \$ara la evaluaci3n de su 1esti3n, as\$ectos estos, relacionados con las 8 3T.

Tambi3n relacionados con las 8 3T, se identi4caron 5CD tales como el uso de los recursos, ener13ticos, materiales, la \$revenci3n de emisiones 2 el reciclado de los insumos, as\$ectos estos claves en la 1esti3n ambiental del sector T+C K4&, L.

Dn el caso de los recursos ener13ticos, se tienen en cuenta, la sustituci3n de ordenadores \$ersonales \$or otros Fue consumen menos ener13a, denominados clientes 3i1eros, instalaci3n de a\$licaciones \$ara la administraci3n de la ener13a en las com\$utadoras de escritorios, uso de a\$licaciones de virtuali<aci3n \$ara eFecutar varios sistemas o\$erativos en un mismo servidor 2 reducir el n3mero de consumo de ener13a en los centros de datos.

Dn el uso de los recursos materiales, la \$revenci3n de las emisiones 2 el reciclado de los recursos se tienen en cuenta Fue la ma2or3a de los materiales utili<ados en la 4abricaci3n de los di\$ositivos, accesorios, insumos 2 eFui\$amamientos in4orm3ticos \$rovienden de recursos no renovables.

3or otra \$arte, estos \$rodutos, durante todo su ciclo de vida, tanto en la 4abricaci3n, en el trans\$orte 2 en su uso, emiten 1ases de e4ecto invernadero. - tro elemento a tener en cuenta es el acortamiento de su ciclo de vida, \$or la in4uencia

Tabla 1.
Factores Críticos de C0ito asociados a la dimensi3n ambiental.

Dimensi3n	Factores Críticos de C0ito
Ambiental	Uso de los recursos materiales
	Insumos reciclados
	Uso de los recursos energéticos
	Uso de los recursos hídricos
	7. Mantenimiento de la biodiversidad
	3. Prevención de la contaminación, las emisiones y los residuos
	Atención a las discrepancias medioambientales
	3. Producción ecológica
	Atención a la reforestación

5uente. Hos autores.

Tabla 2.
Evaluaciones de los 5CD de la dimensi3n econ3mica.

CD	E	lo	'e	'm
Reducci3n de los costos	*	"	"	*
Disminuci3n del presupuesto	'	'	'	'
Ahorro de los recursos	*	'	'	'
Ventas de servicios	=	"	'	'
7. Mejoramiento de las condiciones de trabajo	=	"	'	'
Inversiones en infraestructura	=	"	'	'
Reducci3n de los inventarios	'	'	'	'
Distribuci3n de los productos	=	"	'	'
Reducci3n de riesgos	4,8%	'	'	'

5uente. Hos autores.

de ciclos cortos de innovaci3n, la publicidad entre otros factores, lo que conduce a la sustituci3n de los mismos a medida que van desapareciendo, por lo que las empresas deben tener en cuenta la reutilizaci3n de los componentes de estos dispositivos.

Hoy en día, los 5CD identificados tienen relaci3n con el entorno en el que se encuentra enclavada la empresa y la situaci3n con los recursos hídricos que atraviesa el país. La empresa cuenta con muchas entidades de las TIC que abarcan un gran espectro de actividades, y de estas cuatro, la presencia de masa crítica, en una zona especial para el desarrollo del país, por esta razón se relacionan los 5CD relacionados con la atenci3n a la reforestaci3n, las discrepancias ambientales, la biodiversidad.

Por otra parte, Cuba atraviesa una sequía prolongada, de muchos años, y por su carácter insular, la disponibilidad de agua, depende del almacenamiento de las precipitaciones, por lo tanto, el uso de los recursos hídricos que es considerado como un 5CD dentro de la empresa. La Tabla 1 muestra los 5CD identificados para evaluar la dimensi3n ambiental.

Una vez identificados los 5CD, los criterios para su evaluaci3n coinciden con los definidos en el artículo 4.º del presente artículo 2 representados en la ecuaci3n 1.º #.

Hoy se calcula el número de puntos, a través de la ecuaci3n 1.º # 2 se realiza la selecci3n de los mismos a través del método aplicado en el artículo 4.4. Estos evaluaron cada uno de los 5CD en la escala mostrada en la Tabla 2 del artículo 4.º.

La Tabla 2 muestra el valor promedio (V_{ij}) de las evaluaciones que emitieron los puntos a cada 5CD de la dimensi3n econ3mica en los criterios definidos.

Después de aclarar que los autores calcularon el coeficiente de variaci3n (C_v) de los juicios emitidos por los puntos para

cada 5CD en todos los casos este se comparó y se debió de ser menor a 1, valor que indica que hubo concordancia entre estos.

A continuaci3n, se determinó el peso asociado a cada criterio de evaluaci3n de los 5CD a través del proceso de la jerarquizaci3n analítica. Se normalizó cada uno de los (V_{ij}) a través de la ecuaci3n 2.º # mostrada en el artículo 4.º.

Hoy se calcularon los índices de criticidad (I_{ci}) para cada uno de los 5 factores críticos de C0ito de las dimensiones econ3mica, social y ambiental. Los resultados se muestran en las figuras 1, 2 y 3.



Figura 1. Índices de criticidad de los 5CD asociados a la dimensi3n econ3mica.

5uente. Hos autores.



Figura 2. Índices de criticidad de los 5CD asociados a la dimensi3n social.

5uente. Hos autores.



Figura 3. Índices de criticidad de los 5CD asociados a la dimensi3n ambiental.

5uente. Hos autores.

Tabla *.

Clasi4caciBn de los 5CD asociados a la dimensiBn econBmica.

' rioridad	! " E	" rriticidad
)	D0\$ortaciBn de \$productos	7 u2 alta
!	P entas de servicios	7 u2 alta
'	-nversiones en in4aestructura	7 u2 alta
4	7 e\$oramiento de las condiciones de trabajo	7 u2 alta
,	Ahorro de los recursos	Alta
%	ReducciBn de los costos	Alta
*	ReducciBn de los inventarios	Alta
8	DifecuciBn del 3resu\$uesto	7 edia
=	ReducciBn de rieslos	7 edia

Suente. Hos autores.

Tabla 8.

Clasi4caciBn de los 5CD asociados a la dimensiBn social.

' rioridad	! " E	" rriticidad
)	5ormaciBn de los trabajadores	7 u2 alta
!	(e!uridad 2 salud de los trabajadores	7 u2 alta
'	3rotecciBn de los derechos de los humanos	Alta
4	A\$oto al estado 2 al 1obiero	Alta
,	-nvolucramiento con la comunidad local	Alta
%	Relaciones de trabajo	Alta
*	Com\$ortamiento anticorru\$ciBn	Alta
8	Consumo res\$onsable	Alta
=	Derecho 2 res\$eto al consumidor	Alta
)"	3romociBn de la diversidad 2 de la eFuidad	Alta
))	(alud 2 se!uridad del consumidor	Alta
)!	8 arant\$a de em\$leo	Alta
)'	Com\$ortamiento anti com\$etitivo	Alta

Suente. Hos autores.

Tabla =.

Clasi4caciBn de los 5CD asociados a la dimensiBn ambiental.

' rioridad	! " E	" rriticidad
)	Uso de los recursos ener1Gicos	7 u2 alta
!	Uso de los recursos hidr; ulicos	7 u2 alta
'	Uso de los recursos materiales	7 u2 alta
4	3roducciBn ecolBlica	Alta
,	3reveniBn de la \$oluciBn, las emisiones 2 los residuos	Alta
%	7 antenimiento de la biodiversidad	Alta
*	AtenciBn a disre\$ancias medio ambientales	Alta
8	AtenciBn a la re\$orestaciBn	Alta
=	-nsumos reciclados	Alta

Suente. Hos autores.

Finalmente, los autores, \$riori4aron 2 clasi4caron la criticidad de los 5CD, teniendo en cuenta la escala ordinal de valores \$ro\$uesta en el e\$9!ra4e 4.8, se!In muestran las Tablas *, 8 2 =.

Como muestran los resultados de la a\$licaciBn del \$rocedimiento, de los ') 5CD de4inidos, el !=R obtuvo la clasi4caciBn de criticidad mu2 alta, 2 deber;n ser los \$riori4ados \$or la 1erencia de la em\$resa al evaluar el com\$ortamiento Gico, socialmente res\$onsable de la or1ani4aciBn. Hos 5CD m; s cr4icos 4ueron la 4ormaciBn de los trabajadores 2 uso de los recursos ener1Gicos, se!uidos \$or la e0\$ortaciBn de \$productos 2 servicios.

(olo dos de los 5CD asociados a la dimensiBn econBmica, obtuvieron la clasi4caciBn de criticidad media, 4ueron los casos de la e!ecuciBn del \$resu\$uesto 2 la reducciBn de los rieslos.

- tro elemento interesante del estudio, es Fue el =%*R de los 5CD de4inidos 4ueron clasi4cados con criticidad de mu2 alta 2 alta, lo Fue indica Fue la 1erencia deber; tener en cuenta la ma2or\$a de los 5CD cuando eval!en el com\$ortamiento Gico, socialmente res\$onsable 2 sostenible de la entidad.

0. " onclusiones

DI an; lisis de los 5actores Cr4icos de C0ito es uno de los m4todos m; s utili4ados en la actualidad en di4erentes; mbitos de la vida em\$resarial. Ha de4iniciBn de los 5CD Fue \$ermitan evaluar el com\$ortamiento Gico, socialmente res\$onsable 2 sostenible de una or1ani4aciBn es vital, en una sociedad, donde cada ve< m; s los ne!ocios 2 directivos toman conciencia de la im\$ortancia de 1enerar valores sociales 2 ambientales unidos a los econBmicos.

DI \$rocedimiento \$ro\$uesto en el \$resente trabajo \$ermita \$riori4ar los 5CD \$ara la or1ani4aciBn a trav4s de un 9ndice de criticidad, com\$uesto \$or tres criterios de evaluaciBn, a los Fue son asi4nados \$esos Fue a trav4s de un m4todo multicriterio, e\$sec9!icamente el 3roceso de la 6erarFu\$u Anal9ica 36A#.

DI \$rocedimiento 4ue a\$licado en una or1ani4aciBn Fue \$resta servicios in4orm;ticos lo Fue \$ermitiB \$riori4ar 2 clasi4car los 5CD \$ara lue!o evaluar el com\$ortamiento Gico, socialmente res\$onsable 2 sostenible de la entidad.

5ueron anali4ados ') 5CD, distribuidos \$or las dimensiones, econBmica, social 2 ambiental, 2 a los cuales se les calculB su 9ndice de criticidad a trav4s de la evaluaciBn del im\$acto sobre los ob4etivos, su \$robabilidad de C0ito 2 la \$osibilidad de mediciBn.

De los 5CD anali4ados el !=R 4ueron clasi4cados con mu2 alta criticidad, el %4,, R con alta criticidad 2 solo el %, R con criticidad media. Dsto \$ermitiB a la direcciBn de la em\$resa diri!ir su atenciBn 2 recursos \$ara los 5CD con ma2or 9ndice de criticidad.

DI \$rocedimiento es a\$licado actualmente en otros sectores econBmicos de la sociedad cubana, lo Fue \$ermitir; me!orar continuamente cada uno de sus \$asos 2 contrastar los resultados obtenidos entre entidades con di4erentes ob4etos sociales.

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Comparative study of the mechanical properties of the polyester resin reinforced with bamboo fiber as the substitute material for glass fiber

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Abstract

This research has carried out a mechanical characterization of two types of composite materials- resin polyester reinforced with glass and bamboo fiber. Tests performed tensile, flexural and impact tests according to ASTM. The bamboo fibers were obtained manually and subjected to a chemical treatment with sodium hydroxide to improve their compatibility with the polyester matrix. The specimens were fabricated with mass concentrations of bamboo fiber of 0%, 20% and 40% and polyester reinforced with glass fiber of 0%, 20% and 40%. The mechanical properties of these composite materials were compared with the polyester matrix without reinforcement in order to determine the mechanical contribution of both fibers to the matrix.

Keywords: Glass fiber; bamboo fiber; composite material; mechanical properties; polyester resin.

Estudio comparativo de las propiedades mecánicas de la resina poliéster reforzada con fibra de bambú, como material sustituto de la fibra de vidrio

Resumen

En esta investigación se llevó a cabo una caracterización mecánica de dos tipos de materiales compuestos- resina poliéster reforzada con fibra de vidrio y resina poliéster reforzada con fibra de bambú y se realizaron ensayos de tracción, flexión e impacto siguiendo las normas internacionales ASTM. Las fibras de bambú fueron obtenidas de forma manual y se sometieron a un tratamiento químico con hidróxido de sodio en masa. Las muestras fueron elaboradas con concentraciones en masa de fibras de bambú de 0%, 20% y 40% y resina poliéster reforzada con fibras de vidrio de 0%, 20% y 40%. Las propiedades mecánicas de estos materiales compuestos fueron comparadas con la matriz de poliéster sin reforzar con el fin de conocer el aporte mecánico que le hacen las fibras a la matriz.

Palabras clave: Fibra de vidrio; fibra de bambú; materiales compuestos; propiedades mecánicas; resina poliéster.

1. Introducción

La industria ha fortalecido la producción de diversos materiales sintéticos con la ayuda de nuevas tecnologías. Su evolución ha desarrollado también el uso de materiales reforzados con diferentes tipos de fibras, el caso más común

es el de la fibra de vidrio, ya que sus propiedades han mejorado la resistencia mecánica, actuando como refuerzo en una matriz polimérica.

Tomando conciencia del impacto ambiental generado por el uso de materiales sintéticos y los altos valores de energía involucrados en su elaboración y procesamiento, se realizó el

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análisis comparativo de las propiedades mecánicas de materiales compuestos al utilizar la fibra de bambú como material sustituto de la fibra de vidrio en una matriz de poliéster.

Como resultado de una creciente conciencia de factores ambientales en el mundo, principios de sostenibilidad, ecología industrial, química e ingeniería, integrados dentro del desarrollo en la nueva generación de materiales compuestos, productos y procesos; sin dejar atrás fue la industrialización de ciertos procesos, se ha venido impulsando la inversión en investigación y desarrollo utilizando fibras naturales como una alternativa viable a los compuestos sintéticos.

El estudio titulado "Estudio comparativo de las propiedades mecánicas de la resina poliéster reforzada con fibra de bambú como material sustituto de la fibra de vidrio" el cual se desarrolló con el apoyo del Kruzo de Investigación en 9 áreas de ingeniería, K+9, de la Universidad Tecnológica de Pereira, Facultad de Tecnología en la línea de Soluciones con el apoyo de C, 6 C+BNC+A) mediante la formación de 5 eventos investigadores" (1) (4).

2. Metodología

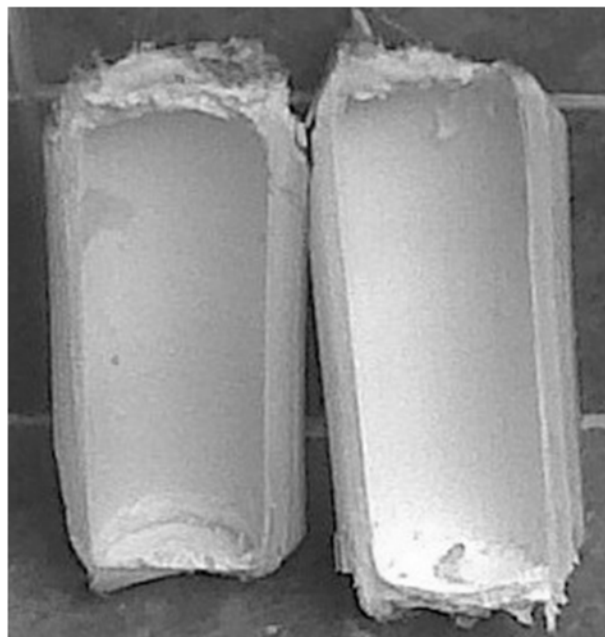
2.1. Fabricación de las muestras

El proceso de extracción de la fibra de bambú es totalmente manual, las fibras utilizadas fueron seleccionadas de la parte interna del tallo de culmos ver H0. (# de la base 2 sobre base, por ser las más resistentes, se dio la investigación de 9 orono et al. (11)) y retiraron los nudos de la cáscara de los canutos y estas muestras se dejaron sumergidas en agua durante 14 horas rotativas de la luz solar a temperatura ambiente. Posteriormente al tiempo de remojo se realizó un proceso de maceración con el fin de facilitar la separación de las fibras fue el trabajo manual en forma de hilos tal como se presenta en la H0. !.

A las fibras de bambú se les realizó un tratamiento químico alcalino mediante el uso de hidróxido de sodio NaOH en una solución acuosa con 2 en masa. Este tratamiento es ampliamente usado para modificar la estructura molecular celular, cambiando la orientación de las regiones cristalinas de alto empaquetamiento de la celulosa y formando una red amorfa en donde las micromoléculas de celulosa son separadas en grandes distancias y los espacios son llenados por moléculas de agua. Las moléculas reactivas restantes forman grupos de fibra; lulaP, PNa entre las cadenas moleculares de celulosa. MN ocasionando fue se reducen los grupos hidroxilo y aumentando la propiedad de resistencia a la humedad de la fibra.

Como efecto adicional del tratamiento, también se eliminan ciertas cantidades de hemicelulosa, lignina, sctina y materiales que cubren la fibra. ceras y aceites. MN Este fenómeno termina aumentando la superficie efectiva de la fibra para una mejor adhesión con la matriz MN.

Para garantizar una aceptable deshumidificación por parte de las fibras de bambú, estas fueron expuestas en estufa a una temperatura de 1°C durante un periodo de dos horas, el carácter hidrofóbico de la resina poliéster es un factor que



H0ura (. Parte interna del tallo culmo#
Fuente: Laboratorio SroSia



H0ura !. B/tracción de la fibra de bambú (# bambú del árbol botánico UTL, !# Corte del bambú, % B/tracción manual de la fibra, 4# Fibras sin tratamiento químico.

Fuente: Laboratorio SroSia

debe considerarse para obtener una buena compatibilidad fibra-matriz y es por esta razón que las fibras se tratan químicamente.

La elaboración de las probetas que mediante el proceso de extracción manual fue consistente en realizar capas consecutivas de poliéster, diluidas con catalizador 9 BRL#al (> de su masa, 2 fibra orientada aleatoria) y de un tiempo de curado de 14 horas para retirarlas del molde. Luego las probetas fueron sometidas a 8°C durante tres horas en un horno según la recomendación del fabricante de la resina.

Los ensayos mecánicos a tracción y flexión se realizaron mediante la máquina universal de ensayos Instron 1130 en el

Tabla 1.
Cantidad de muestras ensayadas.

Bnsa2o	Loli; ster re3or7ado con 3bra de bambD	Loli; ster re3or7ado con 3bra de vidrio	Loli; ster sin re3uer7o	Total
Tracción	15	15	5	35
flexión	15	15	5	35
Impacto	5	5	5	15

Fuente: Elaboración propia

laboratorio de la empresa Andercol S.A. localizada en la ciudad de Bogotá, Colombia mientras fue el ensayo a impacto se llevó a cabo en la Universidad Tecnológica de Pereira en el laboratorio de tribología, 2 a 10 muestras seleccionadas fueron llevadas a un microscopio electrónico de barrido (SEM) en la Universidad de Caldas en el Instituto de Investigaciones en Biotecnología.

2.2. Ensayo a tracción

El ensayo consistió en someter una probeta a una carga uniaxial gradualmente creciente es decir, estática hasta que ocurra la falla. Se siguió la norma ASTM D 638 con una velocidad de ensayo de 1 mm/min. La longitud de prueba de 8 mm.

2.3. Ensayos a flexión

Este ensayo consiste en colocar la probeta sobre dos apoyos y cargarla mediante un punzón situada a media longitud entre los apoyos de 8 mm, según la norma ASTM D 790. La probeta fue flexionada hasta que ocurriera rotura en la superficie superior con una velocidad del cabezal móvil de 1 mm/min.

2.4. Ensayo a impacto Izod

Este ensayo consiste en colocar una probeta empujada en posición vertical en un extremo, e impactarla de acuerdo a la norma ASTM D 256. Las dimensiones de las probetas (10 mm de largo, 10 mm ancho y 2 mm de espesor). Para la realización del ensayo en la máquina de ensayos de impacto de la Facultad de Ingeniería Química de la

Universidad Tecnológica de Pereira. Se buscó en la ranura concentrar el esfuerzo, minimizar las deformaciones elásticas y direccionar la fractura hacia la parte superior.

2.5. Microscopia de barrido EM

Se llevó a cabo en el microscopio de barrido SEM de alta resolución modelo SUANTA 3500 de HB+ con magnificaciones entre 1200x y 10000x.

3. Resultados y análisis

En total se ensayaron 88 muestras distribuidas de la siguiente manera, Tabla 1.

Seis (6) probetas utilizadas para tracción y flexión corresponden a 6 muestras ensayadas para cada porcentaje de resina. Las propiedades mecánicas se presentan en la Tabla 2.

3.1. Importancia mecánica a tracción

De la Tabla 1 se observa que el valor del esfuerzo máximo a tensión presenta una disminución para la resina sin resina comparada con los materiales compuestos fabricados con fibra de bambú y en embarco, al comparar el esfuerzo máximo a tensión entre las distintas formulaciones de resinas reforzadas, no se aprecia una variación significativa del mismo a medida que se incrementa el porcentaje en masa de resina. Las muestras reforzadas con resina presentaron una resistencia a la tensión máxima de 11,1 MPa, 11,1 MPa y 11,1 MPa respectivamente.

En los alcances del actual trabajo no se evaluaron compuestos con mayores concentraciones de fibra, debido a que la elaboración de las probetas por medio de procesos manuales y las características de las fibras vegetales hacen difícil su manipulación a altas concentraciones; para aumentar el porcentaje de resina en estos casos, se sugiere utilizar técnicas como la inyección o la transferencia de resina asistida por vacío en moldes cerrados. En las probetas elaboradas con poliéster reforzado con fibra de vidrio respecto a los valores de la Tabla 1, con resina de 0%, 4%, 8% y 12% en masa de fibra de vidrio, se obtienen valores de esfuerzo máximo a la tracción de 11,1 MPa, 11,1 MPa, 11,1 MPa y 11,1 MPa respectivamente, obteniendo mejor resistencia en las muestras de poliéster reforzado con 12% en masa de fibra de vidrio. Esto es lo esperado, ya que estas

Tabla 2.
Propiedades mecánicas de los materiales ensayados.

Fibra	Concentración en masa (%)	Resistencia a la tracción (MPa)	Módulo de elongación (MPa)	Resistencia a flexión (MPa)	Módulo a flexión (MPa)	Resistencia al impacto (kJ/m²)
-	0	11,1	4,1	11,1	4,1	69,94
Bambú	4	11,1	4,1	11,1	4,1	-
	8	11,1	4,1	11,1	4,1	-
	12	11,1	4,1	11,1	4,1	104,21
Vidrio	4	11,1	4,1	11,1	4,1	-
	8	11,1	4,1	11,1	4,1	-
	12	11,1	4,1	11,1	4,1	461,03

Fuente: Elaboración propia

3.1. Las fibras son mucho más resistentes a las roturas. Fue la matriz. No se reemplazaron los composites con mayores porcentajes de fibra de vidrio, debido a que fue el objetivo principal de la investigación estar enfocado a la comparación del efecto de las dos fibras evaluadas y el mismo porcentaje trabajado de bambú limita las cantidades de fibra de vidrio a adicionar.

Los resultados obtenidos en este estudio, coinciden con algunas conclusiones presentadas por otros investigadores, como es el caso del estudio de las propiedades mecánicas con fibras vegetales procedentes de *9*; /ico llevada a cabo por los investigadores Sasso et al. (2016) a investigación tomé como base una resina *Solite*; reemplazada con fibras de *Oenothera*; n. En dicho trabajo se observó que las propiedades finales de los composites evaluados disminuyen proporcionalmente con el contenido de fibra. En términos generales, en esta investigación se observó un incremento considerable en el módulo de elasticidad de todos los materiales reemplazados respecto al módulo de la resina *Solite*.

3.2. Importancia mecánica a flexión.

Se puede observar que el efecto del contenido de fibra en la resistencia a la tracción aumentó para los materiales compuestos elaborados con ambas fibras utilizadas como refuerzo: vidrio y bambú, respecto al de la matriz *Solite*, como se puede constatar en Tabla 1.

Los resultados obtenidos coinciden con investigaciones provenientes de la India, en donde se obtuvo una resistencia a la tracción de (1,8 y 9 La, con 4" > en volumen de fibra de bambú y un módulo de tracción de %* KLa, Rao et al. (2017) otro estudio llevado a cabo por R. Gurali et al. (2018) con un % > en volumen de fibra, reportó una resistencia a la tracción de (1,8 y 9 La con un módulo de tracción de %1 y KLa; ambas investigaciones concluyeron que el módulo de tracción de todos los composites considerados aumentaba al incrementar la tracción en volumen de fibra en el material compuesto, caso similar al que ha acontecido en este estudio. Cabe mencionar que estas investigaciones emplearon el mismo método de fabricación de las muestras, netamente manual y adicionalmente trabajaron con fibra de bambú.

3.3. Importancia mecánica a impacto Izod.

Adicional a los resultados obtenidos en los ensayos a tracción a tracción, se realizó el ensayo de fractura de impacto a los composites con mayor cantidad de fibra, fueron los que reportaron mejores propiedades mecánicas. En este orden de ideas, se reemplazaron muestras de *Solite* con concentraciones de (1,8 y 9 La en masa de fibra de bambú y (1,8 y 9 La en masa de fibra de vidrio. En total se ensayaron (8) probetas para las pruebas de impacto, distribuidas así: 4 muestras pertenecen al compuesto con fibra de bambú y 4 a la matriz *Solite* sin refuerzo. El *Solite* sin refuerzo obtuvo una resistencia de 1,7 y 4 5m, los resultados muestran que ambos materiales compuestos presentan una tendencia al aumento en su tenacidad respecto al *Solite* sin refuerzo, este aumento se debe a la concentración de fibra de bambú de 4 y 9 La con una resistencia al impacto de (1,7 y 4 5m y a la matriz *Solite* con una resistencia a impacto de 41(,1) %5m.

3.4. Estudio de adhesión fibra matriz

Con el fin de estudiar más de cerca el comportamiento de la interfase entre la fibra y la matriz, se realizaron barridos con microscopía a la zona de fractura de diferentes muestras. Se presentan algunos registros correspondientes al compuesto con un (1,8 y 9 La de fibra de bambú como refuerzo, debido a que este porcentaje reportó los menores valores de resistencia a la tracción. El objetivo de este análisis es confirmar la hipótesis que plantea que en estos casos las fibras no están actuando como refuerzo, sino generando discontinuidades en el material.

En la H0.1 se presenta una superficie de fractura de una probeta de ensayo a tracción con concentración de fibra de (1,8 y 9 La en masa, en la cual se aprecia la ruptura de las fibras por efecto del esfuerzo de tracción aplicado longitudinalmente respecto a su eje principal. Las cavidades señaladas en la figura, corresponden al espacio generado por el deslaminamiento de las fibras, indicando que existe poca adherencia entre el *Solite* y la fibra de bambú lo cual induce su desempeño; esto permite suponer que las fibras utilizadas como refuerzo refuerzan un tratamiento superficial diferente al aplicado para lograr una adecuada interacción fibra matriz. Adicionalmente, se observa que las fibras no están distribuidas homogéneamente en la matriz, lo que puede generar concentraciones de esfuerzos en áreas específicas, nucleando con mayor facilidad otros mecanismos de falla; la causa de esta falta de uniformidad en el refuerzo puede atribuirse al método de preparación manual de las muestras y a los bajos porcentajes de refuerzo que se emplean para el medio de esta técnica.

En la H0.2 se puede evidenciar, la misma muestra de ensayo a tracción, un aumento de orientaciones de fibras en una zona concentradora de esfuerzos, es de notar que luego de la fractura del material compuesto la fibra de bambú se fracturó en varias microfibrillas. Este fenómeno de falla se puede asociar a la presencia de burbujas, orientaciones de deformaciones locales, que pueden inducir al material a fallar antes de que se alcance su resistencia máxima.



H0.1 (9) Microscopía de barrido (SEM) en la superficie de falla de una probeta de ensayo a tensión indicando la distribución no homogénea de las fibras.

Fuente: Laboratorio de Investigación

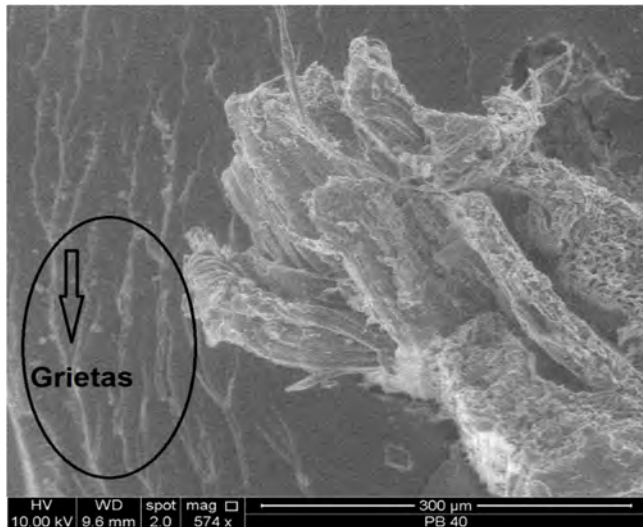


Figura 3. Microscopía BSE en la superficie de fibra de una probeta a 3e/iEn, indicando la presencia de grietas.
Fuente: Laboratorio SroSia

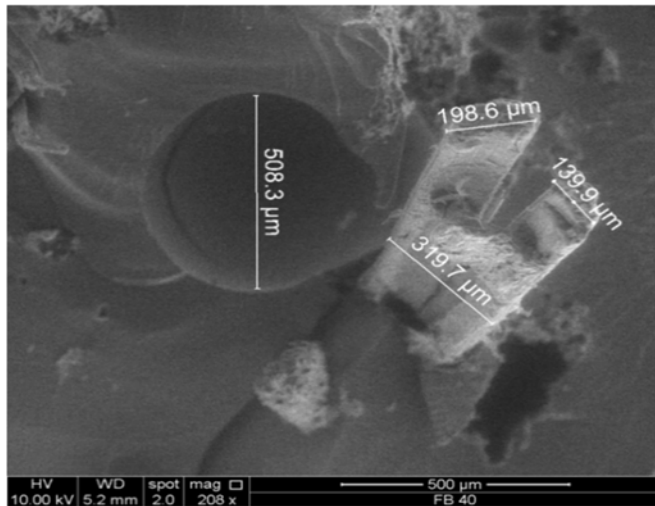


Figura 4. Microscopía BSE de la superficie de fibra del compuesto indicando porosidades en la matriz.
Fuente: Laboratorio SroSia

En las HfOs. 2 y 4 corresponden a micrografías en la superficie de fibra de una probeta de ensayo de 3e/iEn con concentración de fibra de (1,1% > en masa, donde pueden observarse microcavidades generadas por aire atrapado durante el proceso de fabricación de las muestras. Esto también se atribuye a la técnica manual empleada. En la HfO. 4 se observa que la fibra presenta un modo de fractura por falta de adhesión, permitiendo visualizar los vacíos que se formaron al separarse las fibras por deslizamiento y desprendimiento del compuesto de la matriz.

En la microscopía de la HfO. 5 corresponden a micrografías en la superficie de fibra de una probeta de ensayo de 3e/iEn con concentración de fibra de (1,1% > en masa donde se permite evidenciar la morfología de la fibra utilizada, coincidiendo con lo encontrado en la revisión bibliográfica (Núñez, observando que

cada fibra se separa y se ven las microfibrillas, lo que le confiere una morfología hueca en su interior. Esto es una de las causas de su difícil manipulación cuando se pone en contacto con la resina líquida, ya que presenta una tendencia al hinchamiento y absorción.

0. Conclusiones

- Las muestras de Soli; reforzadas con fibras de bambú y vidrio presentaron un aumento del módulo de elasticidad y resistencia a la tracción en la cantidad de fibra utilizada en cada compuesto, pero debido a su aumento de rigidez obtuvieron menor ductilidad en la capacidad de deformación.

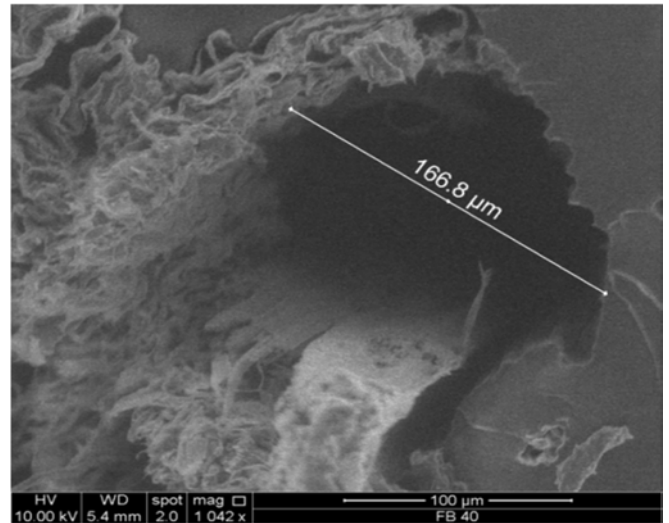


Figura 4. Microscopía BSE en la superficie de fibra de una probeta a 3e/iEn, indicando deslizamiento de fibras.
Fuente: Laboratorio SroSia

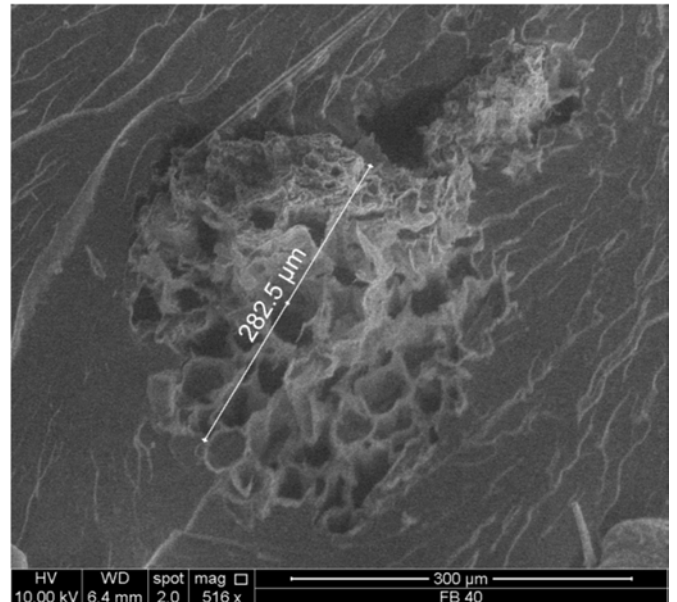


Figura 5. Microscopía BSE, de la superficie de fibra de una probeta a 3e/iEn, indicando la morfología transversal de las fibras.
Fuente: Laboratorio SroSia

Todos los com\$uestos ensa2ados a tracciEn \$resentaron un com\$ortamiento de ti\$o 3rCoil.

- 9 ediante los resultados obtenidos en los ensa2os de tracciEn se observE Fue aFueUos com\$uestos de \$oli; ster re3or7ado con 3bra de bambD con \$orcenta=es en masa de ((."*, (%&%2 (1.!!%> , en ve7 de aumentar la resistencia a la tracciEn de la matri7, \$rodu=eron su disminuciEn \$ro\$orcionalmente al contenido de 3bra.
- A \$artir de la observaciEn microestructural de los com\$uestos re3or7ados con 3bras ve0etales bambD# \$or microscop\$a electrEnica de barrido)B9 #, s atribuye este com\$ortamiento a las discontinuidades 0eneradas \$or la t;cnica de \$rocesamiento manual, =unto con la 3alta de adhesiEn entre la matri7 2 el re3uer7o obteniendo una inter3ace d;bil 2 en al0unos casos 3alta de co\$ulaciEn entre los com\$onentes.
- 6as muestras Fue \$resentaron me=ores resultados a resistencia Dtima a tensiEn 3ueron los com\$uestos de \$oli; ster re3or7ado con 3bra de vidrio con (?,(? > en masa. 6a tendencia observada obedece al aumento de la resistencia con el aumento del \$orcenta=e de re3uer7o.
- Lara los materiales com\$uestos elaborados con ambas 3bras como re3uer7o vidrio 2 bambD# la resistencia a 3e/iEn Dtima aumentE con res\$ecto a la resina sin re3uer7o.
- Bl \$orcenta=e en masa mC/immo ace\$table \$ara la 3ormulaciEn de los materiales com\$uestos de bambD \$oli; ster desde el \$unto de vista de im\$re0nabilidad de la 3bra con la matri7, 3acilidad de 3abricaciEn de \$robetas 2 condiciones de \$rocesamiento manual 3ue de (1.!!%> en masa.
- Bn la observaciEn microestructural \$or microscop\$a electrEnica se com\$ueba la mor3olo0\$a hueca 2 de micro3ibrillas de la 3bra de bambD Fue es la res\$onsable del hinchamiento de la misma cuando estC en contacto con la resina en estado 3uido. Lor esta ra7En, la mani\$ulaciEn de me7clas con ma2or \$orcenta=e de 3bras se hace \$rCcticamente im\$osible \$or \$rocedimientos manuales.
- 6as 3bras ve0etales \$ueden ser utili7adas como 3ase de re3uer7o en materiales com\$uestos de matri7 \$oli; ster en a\$licaciones donde no se reFuieran altas \$restaciones mecCnicas 2 se desee un alto valor est;tico, valores de mEdulo de elasticidad inferiores a 4.4%KLa#.
- Cuando se reFuieran materiales com\$uestos con alta 3e/ibilidad, se \$uede utili7ar resina \$oli; ster re3or7ada con 3bra de bambD 3bra de vidrio. AsQ mismo, cuando se reFuiere un material r0ido, con ba=as e/i0encias en cuanto a su resistencia a la tracciEn, se \$ueden utili7ar 3bras de bambD disminu2endo el costo de materias 3rimas 2 \$ermitiendo el a\$rovechamiento de materiales biodegradables.

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Abstract

This \$a\$er \$resents the o\$timi3ation o4 a00re0ate mi/ ture in the \$roduction o4 \$aver bloc<s throu0h the 4ormulation o4 a linear \$ro0rammin0 model. The \$ro\$osed model aims at reducin0 manu4acturin0 costs, res\$ectin0 the com\$liance 7ith the minimum =ualit2 re=uirements and mechanical.\$h2sical characteristics re=uires b2 the technical standards. The results obtained 7ith the model 7ere used to \$roduce a batch o4 \$products, 7hich under7 ent a \$rocess o4 visual ins\$ection o4 the =ualit2 and laborator2 tests. The results sho7 ed the viabilit2 o4 usin0 a linear \$ro0rammin0 to de4ine the re=uires =uantities o4 ra7 materials to the manu4acturin0 \$rocess o4 Concrete >aver ? loc<s, 7hich 0enerates economic bene4its 4or the industr2 and allo7 s the \$product =ualit2 control as 7 ell.

#ey\$ ords- o\$timi3ation; a00re0ate mi/ ture; \$aver bloc<s; linear \$ro0rammin0.

, \$timi3aci@ de me3clas \$ara la \$roducci@ de \$avimentos a travAs de modelos de \$ro0ramaci@ lineal

Resumen

En este trabajo se \$presenta la o\$timi3aci@ de la me3cla de a0re0ados en la \$roducci@ de blo=ues de ado=uines, mediante la 4ormulaci@ de un modelo de \$ro0ramaci@ lineal. El objetivo es utilizar un modelo de o\$timi3aci@ \$ara reducci@ de los costos de 4abricaci@, res\$etando el cum\$limiento de los re=uisitos m0imos de calidad 2 las caracter\$sticas mec4nicas. 4\$icas re=ueridas \$or las normas t4cnicas. 6os resultados obtenidos con el modelo se utilizaron \$ara \$roducir un lote de \$productos, =ue fue sometido a un \$proceso de ins\$ecci@ visual de las \$ruebas de calidad 2 de laboratorio. 6os resultados demuestran la viabilidad del uso de la \$ro0ramaci@ lineal \$ara de4inir las cantidades re=ueridas de materias \$rimas \$ara el \$proceso de 4abricaci@ de blo=ues de concreto \$ara \$avimentos de concreto, =ue 0enera bene4icios econ@nicos en la industria 2 \$ermite el control de la calidad del \$producto.

>abras%lave- , \$timi3aci@, me3cla e a0re0ados, blo=ues de ado=uines, \$ro0ramaci@ lineal.

1. Introduction

The concrete consum\$tion has been considerabl2 increasin0 in a 0lobal scale.E, ! F. Concrete is used to \$roduce various in4rastructure%related \$products roads, \$orts, \$o7 er \$lants etc.#, buildin0s a\$artments, houses, commercial o4ices, sho\$\$\$in0 malls etc.#, \$avin0s bi<e \$aths, \$ar<in0 lots, side7 al<s, s=uares, \$ar<s, 0ardens etc.#, amon0 others. &several 4actors must be ta<en into account 4or determinin0

and \$re\$arin0 the concrete mi/ ture, considerin0 that the material must meet di4erent mechanical and structural needs, as 7 ell as technical en0ineerin0 environmental and economic%4inancial characteristics.

Considerin0 the \$roduction chain, the search 4or concrete demands the use o4 methods and techni=ues 7hich increase the \$product =ualit2; the e4ficien2 use o4 the ra7 material sand, 7 ater, cement etc.#, the \$productivit2 and, es\$ecial2, the reduction o4 manu4acturin0 costs.

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Several Portland cement concrete properties depend on the characteristics and amount added of its aggregate materials, corresponding to a total weight of the mixture final volume. Thus, the optimization of aggregate mixture is a very attractive option in order to improve the material mechanical properties, in addition to reduce the amount of cement used in the mixture; decrease the overall cost of construction material, and mitigate the environmental impact associated with the concrete production [4].

Considering the manufacturing process of Concrete, which is a product used for the execution of various projects, the quality of the product is not an exception and it is quite dependent on the type and proportion of materials for its manufacture. The saving blocks are concrete structures formed by the union of Portland cement, sand, aggregates and water. According to Hernandez [5], the concrete cohesiveness directly influences the physical and mechanical aspects of the saving blocks, and, therefore, the quality requirements; in addition to determine their manufacturing costs.

The quantitative techniques are among the main techniques used to optimize the aggregate mixture. During the actual manufacturing process, when all raw materials are quantitatively optimized and depend on the optimization purposes, some factors, such as the increase of durability and the reduction of the material costs, may be efficiently obtained [6].

The problem of the optimal raw material mixture for manufacturing the saving blocks should be considered, in essence, as a mixture problem. Such a problem consists in determining the mixture ratio of different input materials for obtaining a final product that meets a set of predefined specifications or standards, so as to obtain a maximization of profit [7]. The mixture problem is well known in the industrial process. Examples may be found in food, oil and chemical industries [8].

The linear programming problem is one of the quantitative techniques used to solve the mixture problem. This allows the resolution of numerous problems when the purpose is to maximize, minimize, or equalize a certain resource, and consists of a good choice when there is a need to define the best combination of materials, forces, and investment allocation, among others, in order to optimize a given system [9].

The purpose of this paper is to use a linear programming for determining the production strategies in the mixture of materials for the manufacturing process of Concrete saving blocks. Thus, it seeks a reduction of product manufacturing costs, respecting the minimum quality requirements and the mechanical, physical characteristics required by the technical standards for the parts used in saving, published by the Brazilian Association of Technical Standards (ABNT).

The research method adopted involved the following steps: definition of the mixture problem; in loco data collection; formulation of linear programming model; linear programming model solution using the solver of Excel; model validation; results implementation with the saving blocks manufacturing; and, final evaluation with visual inspection, and mechanical, physical evaluation of products.

This study is structured into six sections, including this

introduction. Section 1 shows the basic concepts of the mixture optimization problem; section 2 details the manufacturing requirements of Concrete saving blocks for saving; section 3 describes the mathematical model for the production planning; section 4 shows the mathematical results by detailing the development script and the laboratory tests carried out in the pilot production batch, and, finally, section 5 presents the contributions, difficulties and limitations of the present study.

2. The mix problem

Several products are obtained from a mixture of various components, for example, paints, food, chemicals, pharmaceuticals, concrete articles, etc. Considering the product manufacturing process, it is critical the determination of an optimal proportion when using each of the components to reduce manufacturing costs [10].

According to Arenales et al. [11], the mixture problem is to combine materials obtained in nature or remains of others found previously to generate either new materials or products with convenient features. This problem had its first applications in the mixture of gasoline, in which the oil ingredients were mixed for obtaining various fuel qualities [12], and it is considered the precursor of the first applications of the linear programming [13].

A mixture problem can be approached from two perspectives: resources optimization focused on a sustainable development, and resource optimization for the best efficiency of the production process [14].

In general, the mixture problem requires the determination of the optimal mixture or cheaper raw materials available to obey a set of requirements for the final product. As a parameter of the problems, there is the availability of materials, the cost thereof and the minimum quality requirements that must be met [15]. According to Gendolfo et al. [16], the physical formulation of a mixture problem may be given by:

$$\text{Min } \sum_j c_j x_j \quad (1)$$

Subject to-

$$\sum_j x_j = 1 \quad (2)$$

$$\begin{aligned} L_i & \leq \sum_j a_{ij} x_j \leq U_i \quad \forall i \end{aligned} \quad (3)$$

$$x_j \geq 0 \quad \forall j \quad (4)$$

Where x_j corresponds to the amount of each ingredient B_j , c_j is the unit cost of an ingredient B_j and a_{ij} the fraction of

component i in the ingredient B_{Li} and LS_i are the lower and upper limits of quality for each component i .

In practice, the materials are considered much more complex than the standard material problem previously reported. Besides the quality requirements for the final product, other restrictions may be imposed on the problem due to the characteristics of the manufacturing environment, incompatibility of materials, inventory availability, among others. Several of these conditions can easily be added to the model by including new restrictions linear or nonlinear. Thus, the complexity of the model depends a lot on the case to be analyzed (B).

3. Concrete paver blocks manufacturing process

The economic growth in emerging countries such as Brazil, Russia, India, China and South Africa (BRICs) have been causing significant changes in the construction production chain. The concrete consumption is one of the performance parameters of the construction industry. In Brazil it is estimated that in 2013 there will be a demand of 1.2 million m³ (B). Thus, concrete is considered as one of the basic materials for construction infrastructure and buildings, and it is placed as the second most consumed material after water (B).

One of the main applications of concrete is in the manufacture of pavers, used for saving space in lots or circulation of either local vehicles or seaplanes. It is a product that incorporates strength indexes, in addition to facilitate the implementation and maintenance of pavements (B).

The manufacturing process of Concrete pavers is characterized by the concentration of portland cement, sand, particles natural or artificial, aggregates and water, allowing the use of additives and admixtures (B). These elements should be mixed in order to ensure the product compressive strength, durability and reduce the influence of stresses that generate cracks in the surface of the Concrete paver (B). In Brazil, the Technical Norm NBR 12187 Concrete pavers for pavements (B) mentions that the resistance estimated to the blocks compression for saving must be higher than 40 MPa for the movement of commercial vehicles light, and higher than 40 MPa when used for special vehicles heavy. It is pointed out that the product delivered to the customer in a longer time curin0 a0e#than 18 days must have at least 8% of moisture at the time of installation.

Another factor that influences the strength of Concrete paver is the concrete water absorption ratio, which should be less than or equal to 10% (B). It is seen that when the water absorption is very high, the product has a low compressive strength. In the manufacturing process there is also a visual inspection of the products, which should have a homogeneous appearance, regular edges and right angles, free of burrs, defects, delamination and scaling (B).

4. The problem model in

The optimization problem is suggested in order to minimize the Concrete paver manufacturing costs used in the saving of areas with light traffic commercial

vehicles (N). Therefore, the dosage of materials used in the production equipment will be determined, which is commonly referred to as multifunctional vibropress. The consumption control of raw materials is intended to produce a more economical concrete and manufacture products that meet the indexes and visual inspection required by the manufacturing standards (B).

The material that supplies the block machine has a "liter" capacity and sorts up to 48" of aggregates without cement, a parameter used to determine the manufacturing cost of Concrete paver (B).

Other to optimize the dosing time and the material condition Dosage Center with four compartments, four aggregates are selected to the manufacturing process: gravel, crushed stone, garnet stone and sand (B). Aggregates as well as having a cost lower than cement does, gives the concrete a greater stability and durability (B).

The standard trace to produce Concrete paver (B) generally uses the mean sand, coarse sand, gravel, and stone (B). The amount varies according to the climatic conditions of the environment, such as humidity and temperature. It is important to note that the aggregate particle size is important for ensuring the cohesion of concrete and obtaining a satisfactory density (B).

The characterization of the aggregate in the manufacturing process of the concrete blocks depends on the test of rock that influences the mold filling, the maximum size, as well as the grain shape and grading curve. In the optimization process, the material is taken to a particle size analysis of the rock dust. It is a test conducted to characterize the aggregates considering the size and distribution of their particles, thereby reducing water consumption and optimizing the material (B).

For the analysis of the ideal curve and the concentration ranges are used 60% and 100% limit, proposed by Hernandez (B), a reference designed to measure the particle size composition of stone dust. It is used for a series of sieves.

The constraints associated with the optimization of the industrial problem are-

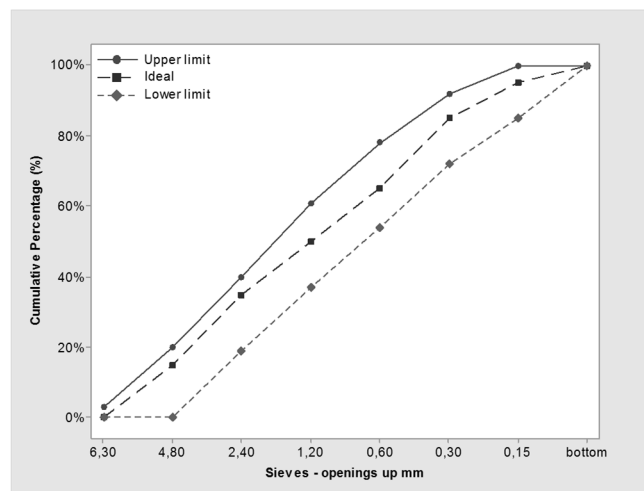


Figure 1. Ideal curve for the analysis of saving manufacturing.

Source: Adapted from (B).

- meeting the limits of the analysis of the dust concentration ranges described by Hernández B-E;
- using at least 1% G sand in the mixture of materials;
- summing the amount of aggregate used, which must be equal to 100%.

The purpose of the optimization problem is to determine the lowest cost for manufacturing concrete, given the mathematical expression and subject to the restrictions described by equations 1, 2, 3 and 4.

$$\text{Min} \sum_{i=1}^n c_i x_i$$

Subject to-

$$\sum_{i=1}^n x_i = 1$$

$$G \leq 1\%$$

$$C_1 x_1 \leq 1\%$$

$$\sum_{i=1}^n c_i x_i \leq 1$$

$$x_i \geq 0$$

Table 1 lists the variables used in the formulation of the optimization model, as well as the related acronyms and cost per mass.

5. Results

For the analysis of the Concrete, two process models were built, that is, AA and BB. During the process of mixing the materials, both coarse sand and fine sand were replaced by gravel, a material of lower cost, AA and BB in the models, respectively. For each of the 8 test samples retained, the percentage mass in each of the sieves was calculated (Table 1), to the nearest 1%, according to the calculation method described in N° R (B-E). It is noteworthy that the results do not appear on some of the screens, which represents 0% of retained accumulated material.

Table 1. Variables of the optimization problem

Variable	Acronyms	Cost (R/ton)
Gravel 0.8mm	>9	18
Gravel 0.8mm mean	>N	18
Gravel 0.8mm small	>>	11
Gravel stone	9R	14
Sand 0.75mm	>	1
Coarse sand	A9	1
Fine sand	AN	1

Source: The authors.

Table 1. Variables of the optimization problem

Variable	1	2	3	4	5	6	7	8	9	10
Gravel 0.8mm	4	4	8	4						
Gravel 0.8mm mean	1	**	+	!						
Gravel 0.8mm small		1	8	!						
Gravel stone			1	!	!					4
Sand 0.75mm		8	!	8	!	(	8	!		
Coarse sand			+	8	**	!	!	!		
Fine sand			*		+	!	+	*	*	*

Source: The authors.

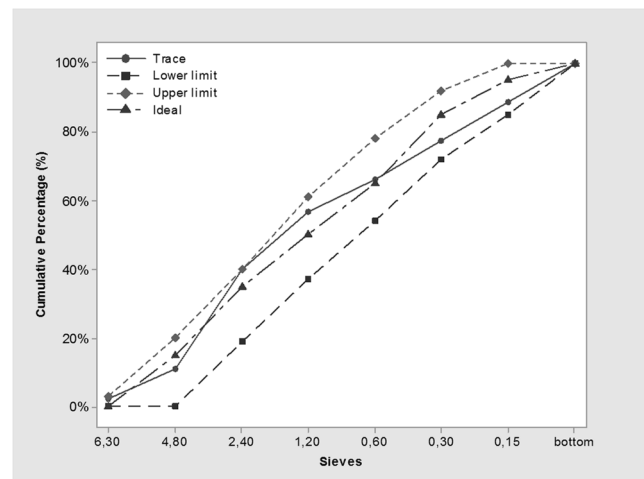


Figure 1. 9 granulometric curves of AA model traces.

Source: The authors.

The estimated cost of the mixtures for AA and BB models was 18.4 R/ton and 18.4 R/ton, respectively. Such values represent a reduction of 1.4% and 1.4% of the trace costs of the current manufacturing processes, which is 18.4 R/ton. When considering that the average daily separation of traits in the plant is 1000 traces/day, it is estimated that the net financial gain in the AA model is equivalent to 104,1 R/month, 41,1 R/month, and 11,1 R/month for the BB model.

For characterizing the best grading combination of aggregates in the manufacturing process of the Concrete, ensuring the physical parameters and quality of the product, it is necessary to calculate the mixture of sand, stone dust and gravel, so that an average is determined and it meets the required curve by Hernández B-E.

The grading curve of the AA model H10.1% showed a high amount of thick materials, which implies a high strength, but with a poor quality finish. A linear trend of the grading curve is seen, given the limits for the manufacturing process of the Concrete. It is a hypothesis of behavior that will provide a product with greater resistance and good quality.

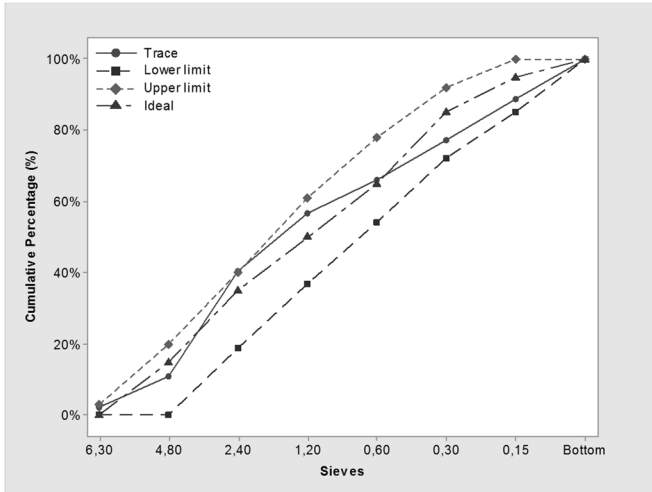


Figure 3. Granulometric curves of model traces.
Source: The authors.



Figure 4. Concrete cover blocks for 8 visual inspection and laboratory tests.
Source: The authors.

The mixtures of aggregates quantities determined for AA and ?? models are used to produce a batch of products. It shows the products made with the current trace, represented by N, AA trace A and ?? trace B, which subsequently went through a process of visual quality inspection via point of a homogeneous appearance, regular edges and straight angles, free of burrs, defects, delamination and scaling. In addition, the products were sent for laboratory tests that allowed determining the compressive strength index of the Concrete cover blocks, carried out with the support of the guidelines of Materials Laboratory, at the State

University of Nariño.

The products manufactured with AA trace showed an acceptable physical quality. The product quality is inferior to both tests, A and N; this is due to the excess of moisture in the ?? trace, because, as highlighted by Dozon et al., the excess of water can compromise the finishing block, affecting its texture and even the color. For calculating the product average strength, a compressive stress expressed in $N/mm^2 < 0.4$ was adopted; equation (1) describes it.

$$P = \frac{F}{A} \quad (1)$$

where:

P is the pressure on the product;

F is the applied force on the surface;

A is the total area where the force is applied.

The product loading area is $100 \text{ mm} \times 100 \text{ mm}$ an area equivalent to the size of the auxiliary boards responsible for the force applied to the specimen. In order to evaluate the compression strength index, three tests were performed 8, 15 and 25 days after production. The results are shown in Figure 5.

The first test specimen of 8 days showed that the resistance in both AA and ?? trace was higher than the current trace, A and B, respectively. In the analysis of the 15 days after production, it was found that the resistance index performance was A and B lower compared to the current trace. The tests carried out in 25 days showed that the product resistance ratio of AA and ?? traces were slightly higher than the product N behavior illustrated in Figure 4. The results validate the hypothesis, that is, it is viable to replace the sand by gravel, a raw material which reduces the costs of the manufacturing process, and maintains the physical and mechanical characteristics of the Concrete cover blocks.

Another advantage seen in AA and ?? models is that with the initial resistance higher than N trace it is possible to deliver products with less curing time to the customer, a situation that increases satisfaction and meets the requirements for the minimum resistance index of $8 N/mm^2$ required by the RIRB for the product installation.

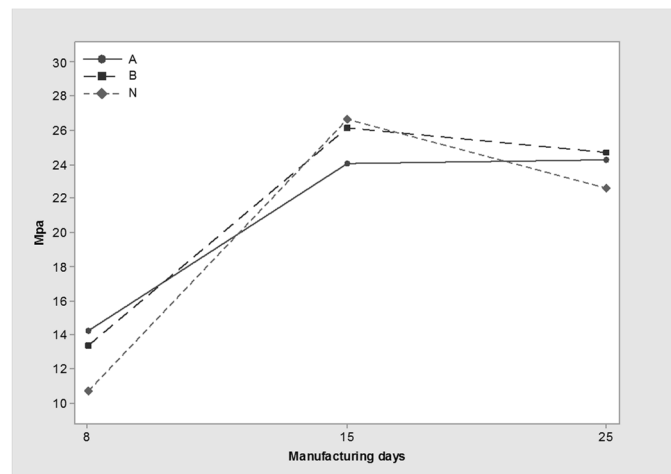


Figure 5. Test curve with 8, 15 and 25 days of curing time.
Source: The authors.

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Association of bodily discomfort with occupational risk factors in poultry slaughterhouse workers

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Abstract

Brazil is classified as the second largest world chicken meat producer and leading exporter. This study aimed at analyzing the characteristics of bodily discomfort in poultry slaughterhouse workers, and its associations with the occupational risk factors. The study included 312 workers, 207 females and 105 males. A body map for evaluating discomfort and an interview regarding organizational issues and criteria of the OCRA method were used. Descriptive statistics and Chi-square test ($p \leq 0.05$) were used. It was found that 85.9% of respondents performed repetitive tasks, 98.1% took rest breaks, 44.6% performed job rotation (2-7 tasks), 40.4% used tools and 62.5% felt cold. Additionally, 71.2% felt discomfort in at least one body region and the body regions most frequently cited were shoulders (50.3%) and arms (34.3%). There was association between body discomfort and individuals' sex ($p < 0.001$), task characteristics (repetitive and non-repetitive) ($p = 0.001$), use of tools ($p = 0.008$) and perception of cold ($p < 0.001$).

Keywords: bodily discomfort; poultry slaughterhouse; repetitive tasks; ergonomics; musculoskeletal disorders.

Asociación entre las incomodidades corporales y los factores de riesgo laboral en trabajadores de mataderos de aves

Resumen

Brasil es el segundo mayor productor de aves del mundo y líder en exportación. Este trabajo tiene el objetivo de investigar las causas de las incomodidades corporales y los factores de riesgo laboral entre los trabajadores de mataderos de aves. El estudio abarcó 312 trabajadores, 207 mujeres y 105 hombres. Se utilizó el mapa del cuerpo humano para evaluar las incomodidades corporales, una entrevista sobre temas organizacionales y el método OCRA. Se aplicó estadística descriptiva Chi-cuadrado ($p \leq 0,05$). Los resultados apuntaron que 85,9% hacían tareas repetitivas, 98,1% efectuaban pausas, 44,6% realizaban rotación de tareas (2-7 tareas), 40,4% usaban herramientas y 62,5% sintieron frío. Además, 71,2% sintieron incomodidad en alguna parte de su cuerpo. Las más mencionadas fueron hombros (50,3%) y brazos (34,3%). Incluso, se identificó relación entre incomodidad corporal y sexo ($p < 0,001$), características de la tarea (repetitiva y no repetitiva) ($p = 0,001$), uso de herramientas ($p = 0,008$) y percepción de frío ($p < 0,001$).

Palabras clave: incomodidades corporales; matadero de aves; tareas repetitivas; ergonomía; trastornos musculoesqueléticos.

1. Introduction

According to the United States Department of Agriculture, in October 2015, Brazil has become the second largest producer of broiler meat in the world, overtaking China, and remaining as leader in exportation of this type of meat [1].

Many poultry processing jobs are physically demanding and involve factors that increase the risk of developing a Musculoskeletal Disorders (MSDs) [2]. Reenen et al. [3] found that the peak and cumulative discomfort could predict future musculoskeletal pain in the neck (relative risk - RR 2.56 and RR 2.35) and right or left shoulder (RR 1.91 and 1.90; RR 2.45 and 1.64, respectively).

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The Ergonomics-related risk factors that may lead to the development of MSDs in poultry processing facilities include: repetition, forceful exertion, awkward and static postures, vibration, and cold temperatures [2]. Tirloni et al. [4] found that the majority of the workers of a poultry slaughterhouse in Brazil reported some kind of bodily discomfort (67.2%). According to Tirloni et al. [4] and Reis et al. [5], workers of poultry slaughterhouse perceived more body discomfort in the shoulders (62.6%; 45.0%, respectively) and neck (46.2%; 29.0%, respectively).

The OCRA Checklist method (Occupational Repetitive Actions) was developed to analyze the workers exposure to risk factors of developing upper limb work-related musculoskeletal disorders (UL-WMSDs) [6]. For such, the method evaluates the main collective risk factors (frequency of actions, awkward postures and movements of the upper limbs, excessive use of force, 'stereotypy' or lack of postural variation, inadequate recovery periods) based on their respective duration, and additional factors, such as mechanical, environmental, and organizational factors. Reis et al. [7] applied the method OCRA in a poultry slaughterhouse, and found that 77% of the activities performed by employees were classified as moderate risk, predisposing the workers to developing UL-WMSDs with greater risk of incidence (between 10.8 and 21.5%) for the right side of the body.

Tirloni et al. [4] using the method OCRA found that 87.6% of workers in the poultry slaughterhouse performed repetitive tasks, 86.2% took rest breaks, 82.8% performed job rotation (2-7 tasks), 54.1% felt cold and 61% used tools. However, there was association only between body discomfort and perception of cold ($p=0.035$).

Therefore, the aim of this study was to analyze the perception of body discomfort in poultry slaughterhouse workers and its associations with the individuals' sex, length of time working at the company, task characteristics (repetitive and non-repetitive), performance of rest breaks and job rotation, use of tools, perception of cold and ambient temperature.

2. Materials and methods

The study was conducted in a poultry slaughterhouse in the South of Brazil, with 3,500 workers approximately, distributed in two shifts. The sectors were classified according to the type of ambient temperature: artificially cold (cutting and shipping) (271 workers) and natural (scalding) (41 workers). The daily working time was 8h and 48 min, with 45 min of breaks for meals, 16 min for physiological needs, 8 min of worksite physical exercise, and 25 min for snacks (coffee).

In Brazil, artificially cold environments are those with temperatures lower than 10°C, 12°C or 15°C, according to the climatic zone of the company's location [8]. The company surveyed was located in a bland mesothermal climate zone (artificially cold environment - average temperature between 10 and 15°C). The environment temperature in the artificially cold sectors ranged from 8 to 12°C.

2.1. Participants

The sample was randomly selected. The company provided a list of all the names of the workers, selecting the

fifth employee down the list followed by the tenth name found in the list and so on. The workers were invited to participate in the study, signed the consent form, and followed to a private room to be interviewed. All participants agreed to be part of this study. The study was approved by the Ethics Committee in Research with Human Beings in Brazil, according to the Declaration of Helsinki.

The study included 312 workers, 207 females and 105 males with a mean age of 33.6 years (range 19 to 52 years) and 36.0 years (range 18 to 54 years), respectively. They were employed for 10.2 ± 8.1 years, at least five months and at the most 35 years, with the majority being right-handed (97.1%).

2.2. Instruments

The human body map for the discomfort assessment was used as a measuring instrument [9]. This instrument was adapted by the authors in order to include the following bodily regions: elbow, wrist, hands, knees and feet/ankles. Each worker should report and/or show the body region where pain/discomfort was perceived. Questions regarding data to identify workers, work organization (presence of job rotation, rest breaks and use of tools) and perception of cold were also used. The tools utilized by the workers were classified in two ways: knife/knife-sharpener and other tools: bowl, stamp and pen, fork, bucket, steel spatula, keys, scissors, thermometer, hammer and cleaner.

For the analysis of repetitiveness, the workers were videotaped for five minutes while performing their activities using the criterion of the OCRA method [10] for classification. Repetitive tasks are characterized as cycles (regardless of the duration) with upper limb movements, or repetition of the same work gesture for the majority of the time (over half of the total time) [11]. In order to classify the pauses performed by the workers as poorly distributed during the workday, the following OCRA criteria were considered: the pause could not be performed before the main meal and in the last hour of the workday, and maintaining a proportion of 5:1 between working time and recovery time [10].

2.3. Statistical analysis

Descriptive statistics was used, as well as the Chi-square test, in order to verify the relationship between variables with a significance level of $p \leq 0.05$.

3. Results

Among the 312 workers interviewed, 71.2% reported bodily discomfort in at least one body region among the 14 regions mentioned, and felt most discomfort in the right side of the body ($p<0.001$). The body regions most frequently cited were: shoulders (50.3%), arms (34.3%), wrists (23.4%), hands (21.8%) and lower back (20.5%), as shown in Table 1.

From 222 workers who felt discomfort, 17.1% classified it as very mild / mild, 50.0% as moderate and 32.9% as very strong / strong. The three symptoms most often reported were pain (82.7%), fatigue (42.3%) and tingling (42.7%). According to 61.7% of workers, the feeling of discomfort

Table 1.

Discomfort regions reported by workers. Values equivalent to percentages according to sex (♂=105, ♀=207).

Regions	Bodily discomfort (%)				
	Right	Left	♂	♀	Total
Neck	9.9	9.3	5.7	14.5	11.5
Shoulders	46.5	38.8	35.2	58.0	50.3
Upper back	13.8	9.6	13.3	15.5	14.7
Lower back	19.9	16.0	19.0	21.3	20.5
Arm	30.1	25.0	21.0	41.1	34.3
Elbows	14.7	10.9	9.5	20.8	17.0
Forearms	11.2	9.6	2.9	18.4	13.1
Wrists	19.9	16.0	11.4	29.5	23.4
Hands	19.6	17.0	11.4	27.1	21.8
Hips	0.6	0.6	0.0	1.4	1.0
Thighs	0.3	0.6	1.0	1.0	1.0
Knees	2.9	2.2	3.8	2.9	3.2
Legs	7.4	7.7	5.7	9.2	8.0
Feet/ankles	1.6	1.9	3.8	1.0	1.9
Total	93.7	84.2	55.2	79.2	71.2

Source: The authors.

was felt for over a year. The majority of the workers noticed increased discomfort during work (83.3%), attributing the feeling to the workplace (97.3%).

Among workers who felt discomfort, 64.0% perceived reduction in discomfort due to the rest breaks, 40.1% on weekends, 27.5% at night, 20.7% decreased during the rotation of tasks and/or breaks and 36.0% of workers mentioned that the discomfort did not decrease in any of the questioned situations. More than half of the workers (61.3%) were taking medications in order to be able to work, 63.0% did so on their own and only 8.0% reported having received a medical prescription by the company, with analgesics being the most widely used (50.5%) after anti-inflammatory drugs (19.4%).

Regarding to length of time of working in the company, 34.6% worked in the company for less than 5 years, 27.2% between 5 and 10 years and 38.1% more than 10 years. The majority of workers performed systematically repetitive work (85.9%). Nearly all of the workers (98.1%) took rest breaks (excluding meal breaks) lasting 08 minutes, with a incidence of 1-5 times day, however, most workers took three daily breaks (68.9%). Also found that 60.6% took at least one poorly distributed rest break during the workday (Table 2).

Job rotation was done by 44.6%, and these rotations consist of 2-7 tasks, and most of them (38.1%) performed two tasks during the workday. In this study, the contents of the tasks of each employee were not investigated. Approximately half of the workers interviewed (40.4%) used hand tools and 88.9% of those used knife and knife-sharpener frequently, and 65.6% of them felt discomfort.

In relation to the perception of environmental conditions, it was found that most workers felt cold during the workday (62.5%), and 45.5% felt heat (often and sometimes). Among those who felt hot, 74.5% worked in sectors with natural ambient temperature.

Some workers felt both heat and cold during work (22.8%). The body regions in which the workers felt the coldest were: feet (56.2%), hands (42.8%), whole body (11.3%), back (6.7%), the legs (5.7%) and the trunk (5.7%). It is noteworthy that 86.9% of workers performed their tasks in artificially cold environments.

Table 2.

Association between perception of body discomfort and different occupational variables.

Perception of body discomfort							
Variables	Present		Absent		Total		p
Individuals' sex	n	%	n	%	n	%	
Female	164	73.9	43	47.8	207	66.3	<0.001*
Male	58	26.1	47	52.2	105	33.7	
Length of time working at the company							
< 5 years	77	34.7	31	34.4	108	34.6	0.119
5.1 to 10 years	67	30.2	18	20.0	85	27.2	
> 10 years	78	35.1	41	45.6	119	38.1	
Task characteristics							
Repetitive	200	90.1	68	75.6	44	14.1	0.001*
Non-repetitive	22	9.9	22	24.4	268	85.9	
Rest breaks							
Good distributed	87	39.2	36	40.0	123	39.4	0.894
Poorly distributed	135	60.8	54	60.0	188	60.6	
Job rotation							
Yes	95	42.8	44	48.9	139	44.6	0.326
Not	127	57.2	46	51.1	173	55.4	
Use of tools							
Yes	100	45.0	26	28.9	126	40.4	0.008*
Not	122	55.0	64	71.1	186	59.6	
Perception of cold							
Yes	153	68.9	42	46.1	195	62.5	<0.001*
Not	69	31.1	48	53.9	117	37.5	
Ambient temperature							
Natural temperature	25	61.0	16	39.0	41	13.1	0.089
Artificially cold environment	197	72.7	74	27.3	271	86.9	
Total	222	71.2	90	28.8	312	100	

Test Chi-square *p≤0.05; % related to bodily discomfort; Use of tools – It's knife and knife-sharpener.

Source: The authors.

There was no association between body discomfort and length of time working at the company, performance of rest breaks, job rotation and ambient temperature; however, there was association with individuals' sex, task characteristics (repetitive and non-repetitive), use of tools and perception of cold (Table 2). The results presented in Table 2 indicate that females felt more discomfort than males, and the presence of discomfort was independent of length of time working in the poultry slaughterhouse; the discomfort occurred mainly with workers who performed repetitive tasks, used tools (knife and knife-sharpener) and felt cold. There was no significant difference between the proportion of workers who felt discomfort with those who did not, in relation to the length of time working at the company, rest breaks, job rotation and ambient temperature (natural or artificially cold sectors).

4. Discussion

Tirloni et al. [4] evaluated 290 workers of a poultry slaughterhouse in Brazil and found that the majority of the workers reported some kind of bodily discomfort as well (67.2%). Tirloni et al. [4] and Reis et al. [7] also corroborate with these results, reporting the shoulder region as the most affected in poultry slaughterhouse workers, 62.6% and 45%,

respectively. The same studies found that the neck (46.2% and 29%, respectively) was the second most affected region with discomfort, unlike the present study where the arms (34.3%) were the second most affected.

Bot et al. [12] obtained data from the second Dutch national survey of general practice (391,294 patients at the start of the survey), the results showed that the most commonly reported complaint was neck symptoms (incidence 23.1 per 1000 person-years), followed by shoulder symptoms (incidence 19.0 per 1000 person-years).

The most bodily discomfort complaints were for the right side of the body, which can be justified by the study of Reis et al. [7]. The authors found that the risk of developing UL-WMSDs in the analyzed activities was also higher for the right side of the body. In the present study, the females workers perceived more discomfort than males ($p < 0.001$), however, in the study of Tirloni et al. [4], there was no association between the discomfort and the individuals' sex ($p = 0.136$). In another study with 1,721 workers in Minas Gerais, Brazil, the prevalence of upper-limb musculoskeletal pain was 24.1% among females and 11.0% among males [13]. Females workers who had high domestic workloads, and performed tasks under high strain showed high prevalence of musculoskeletal pain. For females and males workers, a high prevalence of upper-limb pain was reported by those who performed highly physically demanding tasks, and those exposed to poor environmental conditions [13].

In the present study as well as in Tirloni et al. [4] there was no association between body discomfort and length of time working in the company. According to OSHA [2], jobs and tasks that have multiple risk factors have a higher probability of causing MSDs, and poultry processing may lead to the development of MSDs due ergonomics-related risk factors: repetition, forceful exertion, awkward and static posture, vibration, and cold temperatures allied to these risk factors. In poultry slaughterhouse, the risk factors are varied and high; however, the results of our study suggest that working time at the company and the ambient temperature where the activities are realized were indifferent to cause bodily discomfort.

The risk of MSD injury depends on the frequency in which the task is performed, the level of effort required, the duration of the task, as well as other factors [3]. Reis et al. [7] when analyzing 22 tasks performed in a poultry slaughterhouse, considering the five risk categories by the proposed OCRA method, found that 9% were considered high risk, 77% moderate risk and 14% were within a low risk, suggesting that the majority of the slaughterhouse workers were vulnerable to ergonomic hazards due to repetitive movements. Reis et al. [14] using the same method, analyzed 26 work activities and found that 8% were considered high risk, 81% represented moderate risk and 11% were within a low risk. The results of these studies suggest that workers are predisposed to a greater probability of developing UL-WMSDs.

According to Sundstrup et al. [15], there are predominant highly repeatable movements of the upper limbs in poultry slaughterhouses. Several studies used the OCRA method and presented findings classifying the work in the poultry slaughterhouse as repetitive [4,7,11,14] where most of the

activities presented a high risk [11,16,17].

OSHA [2] recommends that the employer should allow pauses in order to provide for recovery of fatigued muscles. The Brazilian Regulatory Standard 36 (NR-36) [18] establishes the minimum requirements for evaluation, control and monitoring risks in activities performed at meat processing industries cites.

The NR-36 advises that for workers who perform activities directly in the production process, which requires repetitiveness and/or static or dynamic neck muscles overload, shoulders, back and upper and lower limbs, distributed psychophysiological breaks should be provided. In contrast, in our study, there was no association between body discomfort and pause performance.

The breaks should be distributed in a manner to avoid the first hour of work, in close proximity with meal breaks or within the last hour of work [18]. In our study, both employees who felt uncomfortable as those do not felt, took rest breaks, good or poorly distributed ($p = 0.894$), similar to the Tirloni et al. [4] ($p = 0.746$).

Studies should be conducted by analyzing in more detail the variables that can interfere in the effectiveness of breaks such as the location where the breaks are performed. NR-36 [18] recommends rest break areas located away from the workstation, with thermal and acoustic comfort, and with banks or chairs and drinking water available. The same norm cites that the break cannot be accompanied by an increase in the individual's rate of production after returning to work, and the pauses cannot be accumulated. Therefore, compliance with this standard requires the monitoring of rest breaks by both employers and employees.

One administrative solution used effectively by poultry processors to reduce the duration and frequency of exposure to risk factors, is the use of a rotation schedule to address high-risk tasks, and design a job rotation schedule in which workers rotate between jobs that use different muscle groups [2]. In the study of Tirloni et al. [4], there was no association between body discomfort and job rotation ($p = 0.385$), similar to the present study. According OSHA [2], job rotation may alleviate physical fatigue and stress to a particular set of muscles and tendons, however, the review study of Leider et al. [19] found that there is inconsistent evidence for recommending job rotation as a strategy for preventing musculoskeletal complaints.

The NR-36 recommends that the abattoir's employer must implement job rotations in the daily journey that provides at least one of the following requirements: alternation of working positions, the muscle groups with activities without requiring repeatability and environmental exposure to noise, humidity, heat, cold, more comfortable; reduction of postural requirements such as elevations, pushups/extreme extensions of body segments, excessive radial/ulnar deviation of the wrist, among others; reducing or minimizing the most frequent static and dynamic forces; reduction of loading, handling and lifting loads and weights and repetitiveness [18].

In slaughterhouses, the rotation is also indicated between tasks with cadence set by machines, treadmills, overhead conveyor with other tasks where the worker can freely determine their pace of work; in activities where workers'

hands are completely wet and it is not possible to use gloves, due to the probability of generating additional risks, rotation to other tasks is advised [18]. Therefore, more detailed and controlled studies about job rotation are required; in order to monitor the actual task performed by employees, as well as analysis those tasks should be performed.

In the present study, the use of knife was associated with bodily discomfort, the workers who did not use knife felt less body discomfort, on the other hand, the study by Tirloni et al. [4] did not find association between these variables ($p=0.303$). The tools should promote the adoption of appropriate postures and movements, ease of use and comfort, in order to not require the worker to use excessive force, pressure, hold, flexion, extension or twisting of the body segments [18]. The NR-36 recommends that the tools should be specific and appropriate for each type of activity, light and efficient.

The handgrip strength can be a predictor of compression syndromes of the upper limbs, since compression of the peripheral nerves of the UL contributes to loss of grip strength [20]. The employers should train employees on knife-sharpening, maintenance schedules and good cutting techniques, whereas as using dull knives result in workers having to apply more force than necessary to accomplish the task [2].

The NR-36 states as preventive actions: sharpening and suitability of tools and equipment; training and orientation of workers, on admission and routinely; as well as the existence of a regular maintenance schedule [18]. More studies on the use of tools in slaughterhouses should be conducted with analysis of the process of sharpening the knives, the use of knife-sharpener, and exchange of knives during the workday and yearly, as well as evaluation of grip strength of those who perform manual tasks during the workday.

In relation to perception of cold, according OSHA [2], use of force in combination with cold temperatures increase the potential of develop MSDs. Corroborating with this study, Tirloni et al. [4] found that the bodily discomfort was associated with the perception of cold of poultry slaughterhouse workers ($p=0.035$).

Many of the operations in poultry processing occur with a chilled product or in a cold environment [2]. Ramos et al. [21] used an infrared camera and found that workers who used knife had the contralateral hand (non-dominant) significantly colder, and this may be due to the handling of refrigerated products. One administrative solution used effectively by poultry processors to reduce the duration and frequency of exposure to risk factors is to minimize exposure to cold [2].

For workers who carry out their activities in artificially cold environments the NR-36 recommends that companies make available system for heating hands near the toilets or rest break areas provide personal protective equipment; provide a rest break after an hour and forty minutes of continuous work, and performance rotation with activity alternating changing environmental exposure, obeying the hygienic and sanitary aspects [18].

4.1. Limitations of the study

The research was performed in only one poultry slaughterhouse, making it impossible to generalize the

results. It was not possible to control and detail some variables, such as the content of the tasks performed by each employee, and monitoring the rest breaks during the workday to check for compliance.

5. Conclusions

In conclusion, the majority of the workers felt bodily discomfort, the right side of the body was the most affected, the regions with the biggest complaints were the shoulders and arms and the symptoms most often cited by workers were pain, fatigue and tingling. Most workers who felt bodily discomfort were taking medication on their own, in which, the analgesic was the most commonly used medication; these workers performed systematically repetitive work, took rest breaks and felt cold; on the other hand, the minority of the employees performed rotation, and used hand tools. The body regions that most workers felt cold were hands and feet.

Body discomfort was associated with individuals' sex, in which was more prevalent in females than in males; also associated with the performance of repetitive tasks, the use of hand tools (knives/knives-sharpener) and the perception of cold by the workers. Lastly, it was found that workers felt bodily discomfort regardless of the length of time working in the poultry slaughterhouse, of the distribution of breaks and performance of job rotation.

The results of this study point to the need for preventive actions in poultry slaughterhouse such as the organization of work (adjust the rhythm of production, the number of employees, and the individual's psychophysiological capacity; conducting rotations containing repetitive tasks and not repetitive, with and without the use of hand tools and in different environments - natural and artificially cold). Also suggests that there is a need to control the sharpening process and replacement of knives, provide training on sharpening of knives, supply gloves, socks and boots with increased thermal insulation and quality.

Finally, the sector of occupational safety and health administration in the poultry abattoirs should enhance and intensify the prevention programs of WSMDs, mainly among females, since they appear to be the most affected with bodily discomfort. The health care systems offered to workers in abattoirs should be improved by providing more accurate diagnoses, recommending an appropriate treatment and advice workers on the risk of abusive ingestion of medicines without prescription.

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Traffic modelling of the video on demand service through N(&

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Abstract

The \$rinci\$al characteristic of the video on demand service through video streaming technology is the consumption of large bandwidths, which is why network planners must consider the service when dimensioning said network. To achieve this goal, one of the tools is traffic engineering and its associated models. Thus, this article presents a traffic model based on simulation through discrete events and developed through the open code software and research on network, denominated ns&. This network describes the abstractions of network elements and the construction process of different evaluation scenarios, independent of the characteristics of the service sought to be analyzed, and the collection and graphic visualization of statistics. Finally, the network presents the analyses of the performance parameters that permit obtaining the minimum network characteristics to support the service.

Key words. Network performance; N(&, simulation; traffic model; video service.

Modelado de tráfico del servicio de video bajo demanda mediante N(&

Resumen

La característica principal del servicio de video bajo demanda a través de la tecnología de video streaming es el consumo de grandes anchos de banda, por lo que los planificadores de redes deben considerar este servicio en el momento de dimensionar dichas redes. Para alcanzar esta meta, una de las herramientas es la ingeniería de tráfico y sus modelos asociados. Así, este artículo presenta un modelo de tráfico basado en la simulación por eventos discretos desarrollado a través del software de código abierto de investigación en redes, denominado ns&. Este describe las abstracciones de los elementos de red, el proceso de construcción de diferentes escenarios de evaluación, independiente de las características del servicio que se desee analizar, y la recolección y visualización gráfica de estadísticas. Finalmente se presentan los análisis de los parámetros de desempeño que permiten obtener las características mínimas de red para soportar el servicio.

Palabras clave. Desempeño de red, N(&; simulación; modelo de tráfico; servicio de video.

1. Introduction

Video streaming is an audiovisual service that permits consumption of multimedia content. This service can be provided through diffusion, point to multi-point, or point-to-point. Its principal advantage lies in not having to download contents onto a computer to be watched later; also, contents can be seen in real time, as with a live recording on television (streaming).

For video traffic through video streaming, will represent 80% of all traffic in 2010, above 40% in 2005. Residential and business consumers and mobile consumers continue demanding advanced video services through all types of network and devices, mainly quality, comfort, content, experience, and price

the two success factors! Therefore, network planners must be able to dimension and update said network to satisfy end users without causing them trauma, besides protecting communication investments in infrastructure.

Among the tools available to network planners and engineers are traffic models as part of engineering, which constitutes an important branch for planning and implementation of communication network, given that they permit reviewing and analyzing the behavior of the traffic generated by these services and applications, and determines the network resources necessary for their implementation. The teletraffic theory is defined as the application of the probability theory to the solution of problems related to

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\$lannin1, \$er3ormance evaluation, o\$eration, and maintenance o3the telecommunication s2tems I, J.

The ns& tool ? as used to conduct this research, ? hich is 3amed ? ithin the tra33ic models based on discrete event simulation accordin1 to the classi3cation \$resented in 14J. These models describe \$henomena in a 1iven moment, ? here each event has a \$peci3ic incidence instant that can be re\$resented on the discrete tem\$oral scale o3the simulation occu\$2in1 a sin1le \$osition and or1ani7in1 chronolo1ical2, ? hich 3acilitates \$rocessin1. 8ach event is an action and its result is the modi3cation o3 state variables, ? hich ma@es them suitable to simulate ? ith \$ro1rammin1 lan1ua1es aimed at ob3ects I% ' J.

The ns& tool ? or@throu1h discrete events, \$ro1rammed total2 in CLL, main2 3ocused on research and educational \$ur\$oses. It is an o\$en so3? are \$ro3ect under the MNU MF; v! license, ? hich is ? h2 users can create or modi32 e0istin1 models. ns& is not onl2 a tool 3or simulation and emulation, it is also a so3? are develo\$ment \$ro3ect 3or research on telecommunication net? or@, ca\$able o3 su\$3ortin1 the latest technologies and in ? hich ? orld& reno? ned universities \$artici\$ate, besides com\$anies and research 1rou\$s aimed at net? or@ I*J. <or these reasons, N(& is the selected tool 3or this research. <urthermore, based on the +888 N\$lorer Di1ital ; ibrar2 searches, it is the most used 3ree tool 3or telecommunication research.

The contribution o3 this article is the develo\$ment o3 a tra33ic model and the evaluation o3 the \$er3ormance o3 the video on demand service HoD# on an 8thernet, throu1h simulation techniEues via discrete events, throu1h the research tool in telecommunication net? or@ o3 the ns& scienti3ic communit2. Additional2, this stud2 \$resents the construction \$rocess o3the evaluation scenarios inde\$endent o3the characteristics o3the service to be anal27ed, see@n1 to o33er the communit2 a re3erence in the construction o3models based on discrete events throu1h ns&.

The develo\$ment metodolo1o2 o3 this research is based on an ada\$ta1ion o3that described in 18J, 3ounded on states and transitions, ? here the 3irst state corres\$onds to the real e0\$erimentation scenario and the transition corres\$onds to the mathematical 3unctions that describe the behavior o3the videos. The second state corres\$onds to the simulation environment and the res\$ective transition re3ers to the to\$olo1ies. The third state corres\$onds to the modellin1 o3 the service throu1h discrete event simulation D8(#, ? hose transition corres\$onds to the model. The 3inal state corres\$onds to the results 2ielded b2 e0ecutin1 the model.

This article is or1ani7ed in the 3ollo? in1 manner. section ! \$resents the real e0\$erimentation scenario and the tools used 3or its construction. (ection , describes the construction o3 the simulation environment in ns&, ? hile section 4 studies the construction o3the model throu1h discrete events in ns&. (ection % describes the anal2sis and results o3 the research. <inal2, section %\$resents the conclusions o3the \$resent ? or@

2. Real experimentation scenario

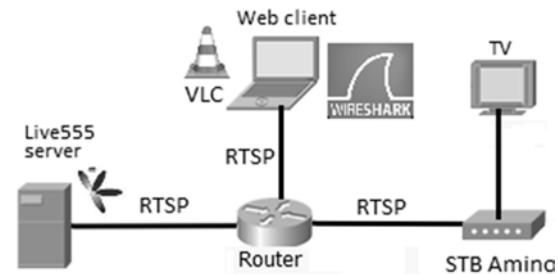
To develo\$ the model, three videos ? ere used ? ith distinct characteristics re1ardin1 duration and mobilit2, ? hich \$ermit a com\$arative anal2sis amon1 them. Table) \$resents their characteristics.

Table).

Characteristics o3the videos

Characteristics of the videos			
	Video 1	Video 2	Video
Duration	=4 s	"= s	!8 s
(i7e	'! .45 O	%8.= 5 O	=.* 5 O
Oit rate	%! 5 b\$s	4., 5 b\$s	! .85 b\$s
Com\$le0it2	5 ovement	5 ovement	; o?
	a\$3reciable	smaller than	mobilit2
	throu1hout its ? hole	video)	
	duration		

Codec. m\$e1!. Container 3ormat. T(Trans\$ort (tream# Resolution.)=!"0)"8". <F(<rames Fer (econd# !=.*. A\$sect resolution.)' . = (ource. The authors.



<i1ure.). (cenario o3HoD e0\$erimentation service. (ource. The authors.

<i1.) \$resents the e0\$erimentation scenario used to ca\$ture the real tra33ic o3the HoD service; the streamin1 server used ? as live%8% ? hich is in char1e o3disseminatin1 \$revious2 encoded multimedia content in the net? or@As streamin1 3o? clients ? e used a set to\$ bo0 (TO# o3internet \$rotocol television +FTH# b2 Amino and a \$ortable com\$uter in char1e o3 ca\$turin1 and consumin1 the multimedia3o? transmitted, usin1 ? ireshar@and H; C tools, res\$ectivel2 I=J. The HoD service is available 3or consumption via internet b2 usin1 a ? eb \$la3orm or also via +FTH direct2 to a television set b2 usin1 an (TO, throu1h usin1 the real 8ime transmission \$rotocol RT(F#

To consume this service throu1h an +FTH net? or@the (TO in \$articular needs the 3les consumed to be in 5 F8M&3ormat. 5 F8M&Trans\$ort (tream# ? hose e0tension is .ts. To obtain this 22se o33le, 3m\$e1 so3? are ? as used. O2 usin1 this so3? are the codecs o3 the 3les ? ere chan1ed 3or e0\$erimentation so that the2 coincided ? ith those used b2 the +FTH & (, these are. m\$e1& 3or video and aac 3or audio; additional2, other \$arameters are con31ured, li@ resolution, a\$sect ratio, and bit rate. <i1. ! sho?s the encodin1 and com\$ression \$rocess carried out on a video 3le ? ith .? mv e0tension b2 usin1 3m\$e1. The chan1e o3 codecs can be seen in video 3rom ? mv! to m\$e1! video and in audio 3rom ? mav! to lib3aac; in addition, the 3le is \$ac@aled in trans\$ort stream T(#. This \$rocess is conducted in the Ubuntu o\$eratin1 s2stem. To achieve ca\$turin1 the tra33ic traces bet? een the server HoD live%8%and the client, the ? ireshar@ \$rotocol anal27er ? as used. This tool is ca\$able o3ca\$turin1 all the tra33ic streamin1 throu1h the device to ? hich it is connected. The 5 F8M& encodin1 standard, ? hich has been used to encode the videos, creates a 3o? throu1h 3our 12\$es o3 data, these are. intra 3rames, \$redictable \$osterior 3rames, bi&directional \$redictable 3rames, and audio, re3erred to as +, F, O, and audio 3rames, res\$ectivel2.

```

root@stcav-Studio-540: ~/live/mediaServer
kb/s
[buffer @ 0x2865ac0] w:1920 h:1080 ptxfmt:yuv420p tb:1/1000000 sar:0/1 sws_param:
[scale @ 0x28c2440] w:1920 h:1080 fnt:yuv420p -> w:720 h:576 fnt:yuv420p flags:0x4
[mpeg2video @ 0x28c1b20] Warning min_rate > 0 but min_rate != max_rate isn't recommen
ded!
[mpeg2video @ 0x28c1b20] impossible bitrate constraints, this will fail
[mpegts @ 0x28cbe20] muxrate VBR, pcr every 3 pkts, sdt every 200, pat/pmt every 40
pkts
Output #0: mpegts, to 'video5.ts':
Metadata:
  encoder      : Lavf53.32.100
  Stream #0:0: Video: mpeg2video, yuv420p, 720x576 [SAR 64:45 DAR 16:9], q=2-31, 5
700 kb/s, 90k tbn, 30 tbc
  Stream #0:1: Audio: aac, 48000 Hz, 2 channels, s16, 150 kb/s
Stream mapping:
  Stream #0:0 -> #0:0 (wmv2 -> mpeg2video)
  Stream #0:1 -> #0:1 (wmv2 -> libfaac)
Press [q] to stop, [?] for help
<figure>!. Chan1e o3 video encodin1 ? ith 33m$e1.
( ource. The authors.

```

The traffic captured through *reshar@* contains all types of information on control, filler, synchronization, etc., besides the distinct types of frames that comprise the video in question and which in the end is the data of interest for the experiment. Hence, it is necessary to use filters in *reshar@* to show only the data of interest. <fig. 1 illustrates the filters to separate the frames from the video into +, F, O, and audio frames. This process helps to clean the data; however, the different frames that make up a video are sent to the network or in interlaced form, that is, a frame tallied as type + may contain in it type F frames, which greatly hinders data extraction; to achieve a complete extraction the software developed in I8J is used.

```

Filter: mpeg-pes.dts and !mpeg-pes.frame_type==2
a! T2se + < rames
Filter: mpeg-pes.frame_type==2
b! T2se F < rames
Filter: mpeg-pes.frame_type==3
c! T2se O < rames
Filter: mpeg-pes.stream==audio-stream
d! Audio < rames

```

<figure>!. <filters in ? reshara@ for the different 5 F8M & frames.
(ource. The authors.

The mathematical characterization detailed process of the traces of traffic, through the probability distribution functions $FD_{<#}$, is shown in I8J and its results are presented in Table 1.

Construction of the simulation environment in " # \$

Three distinct network topologies have been designed in which network performance parameters will be evaluated when streaming previous obtained real traffic in them. These topologies were chosen because they are commonly used in the implementation of AN network, but also with the intention of establishing differences between them as far as network performance parameters, latency and delay. <fig. 4 shows the distinct network topologies used. Topology 1, has two scenarios; the first of these is designed for a network with 10 users, and the second for 100 users, to analyze the performance of the network when information overload exists. The other topology (topology 2) has 10 users each. The number of users was decided, given that based on the analysis of the characteristics of the videos, in all the users simultaneously request any of these videos, traffic is generated in the order of tenths over any of the topologies.

The aim of the simulation is to obtain the results of the performance parameters in the first of cases, that is, in the hypothetical case of all the users requesting the same video at the same time. With this, it is possible to determine the network resources necessary to serve a number of users in the first of cases. Hence, the simulation starts when the server begins to transmit the data required by the user and ends when the video has finished. The element necessary to construct the topology is Topology 2.9 elements.

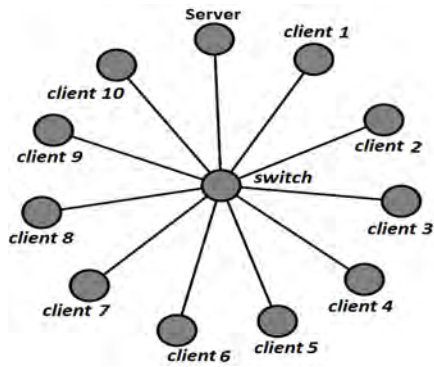
In a real network, we can find computers with network cards; in this, it could be said that nodes exist with network devices. In a network it is necessary to configure the connections among nodes, network devices, and communication channels.

Table 1.

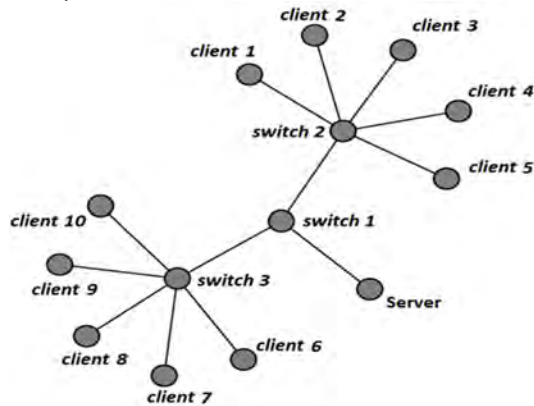
Probability distribution functions characterized by the mathematical behavior of the videos.

		Video1		Video2		Video	
		% & (test)	# & (test)	% & (test)	# & (test)	% & (test)	# & (test)
T2se o3 frames	+	FD<	normal	FD<	normal	FD<	normal
		P	" .4" ! "	P	" .4" ! "	P	" .4" ! "
		Q	" . " , %	Q	" . " , %	Q	" . " , %
	F	R(	" . " , %	R(	" . " , %	R(	" . " , %
		FD<	normal	FD<	normal	FD<	normal
		P	" .) , %8	P	" .) , %8	P	" .) , %8
		Q	" . " 88	Q	" . " 88	Q	" . " 88
	O	R(	" . " 88	R(	" . " 88	R(	" . " 88
		FD<	normal	FD<	normal	FD<	normal
		P	" . " %8	P	" . " %8	P	" . " %8
		Q	" . " , 8	Q	" . " , 8	Q	" . " , 8
		R(	" . " , 8	R(	" . " , 8	R(	" . " , 8
Audio		FD<	normal	FD<	normal	FD<	normal
		P	" .) 484	P	" .) 484	P	" .) 484
		Q	" . " 4 "	Q	" . " 4 "	Q	" . " 4 "
		R(	" . " 4 "	R(	" . " 4 "	R(	" . " 4 "

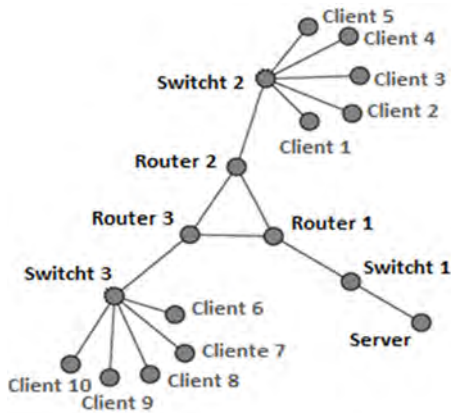
(ource. The authors.



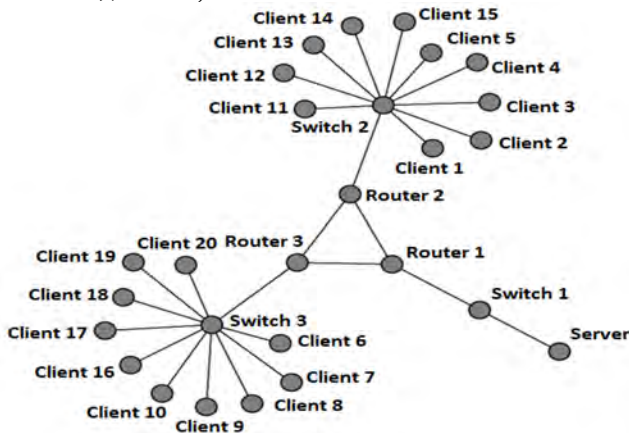
a# To\$olo12)



b# To\$olo12 !



c! To\$olo12 , , scenario)



d! To\$olo12 , , scenario !

<i!ure 4. Net? or@to\$olo1ies 3or case studies.
(ource. The authors.

ns&, the abstraction o3the com\$utin1 device is called Node; the abstraction is re\$resented in CLL b2 the Node class, ? hich \$ermits addin1 3unctionalities, li@a\$a\$lications, \$rotocol stac@, and \$eripheral cards ? ith their associated drivers. A node can be connected throu1h an ob\$ect re\$resentin1 a communication channel; its abstraction is called Channel and it is re\$resented in CLL b2 the class o3the same name.

NetDevices are the net? or@ device abstraction that involve the so3? are controller and simulated hard? are. A net? or@device is installed to enable communication amon1 nodes throu1h the Channels. A node can be connected to more than one channel throu1h multi\$le net? or@devices. The abstraction o3the net? or@device is re\$resented in CLL b2 the class o3the same name.

To\$olo12 hel\$ers \$ermit assi1nin1 \$h2sical addresses, installin1 net? or@devices in a node, con3iurin1 the nodes \$rotocol stac@ and Then T connectin1 the netdevices to the channel. Throu1h the Node Container, node ob\$ects are created ? ithin ns& that ? ill re\$resent the com\$uters in the simulation <i1. %#.

The 3rst line onl2 declares a node container called nodes. The second line calls the Create method in the node ob\$ects and as@ the container to create t? o nodes. The 3ollo? in1 ste\$ in the construction o3a to\$olo12 is to connect the nodes ? ithin the net? or@ <or e0am\$le, to construct a \$oint&o& \$oint lin@ use the to\$olo12 hel\$ers ob\$ect and ? ithin it use a PointToPoint9 el\$er to con3iure and connect the \$oint&o& \$oint net? or@device ob\$ects PointToPointNetDevice# and \$oint&o& \$oint channel hel\$ers FontToPoint9 el\$erChannel#, as sho? nin<i1. ' .

Ne0t, it is necessar2 to have a list o3 the ob\$ects,) et* evic, 3or ? hich a) et* evicContainer is used to mane the tas@<i1. * \$resents the 3nal con3iuration o3the devices and the channel. The 3rst line declares the device container and the second line o3the install method o3the \$oint&o& \$oint lin@ hel\$er ta@s a NodeContainer as \$arameter.

A 3er e0ecutin1 the \$ointTo\$oint.nstall call, ? e? ill have t? o nodes, each ? ith a netdevice and a channel bet? een them.

```
NodeContainer nodes;
nodes.Create (2);
```

<i!ure % Node container.
(ource. The authors.

```
PointToPointHelper pointToPoint;
pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));
```

<i!ure ' . Construction o3\$oint&o& \$oint lin@
(ource. The authors.

```
NetDeviceContainer devices;
devices = pointToPoint.Install (nodes);
```

<i!ure *. <inal con3iuration o3the devices and the channel.
(ource. The authors.

```
InternetStackHelper stack;
stack.Install (nodes);
```

Figure 8. Installation of the protocol stack.
(Source: The authors.)

```
Ipv4AddressHelper address;
address.SetBase ("10.1.1.0", "255.255.255.0");
```

Figure 9. Assignment of IP addresses.
(Source: The authors.)

```
Ipv4InterfaceContainer interfaces = address.Assign (devices);
```

Figure 10. Association of IP addresses.
(Source: The authors.)

```
Simulator::Run ();
```

Figure 11. Run the simulation.
(Source: The authors.)

The following step installs the protocol stack in the nodes. The helper is the `InternetStackHelper`, in charge of installing the protocol stack in the nodes. The `install` method takes a node container object as parameter; when it is executed, it installs the internet protocols in each of the nodes.

Next, we need to associate the node devices to the IP addresses. A helper exists to manage the assignment of IP addresses. Figure 9 shows the code lines that declare an object helper of addresses. By default, the addresses assigned will start at one and will increase one by one. The `ns-2` system at low level remembers all the addresses assigned and will generate an error if by accident the same address is assigned twice.

The following manages associations between IP addresses and the devices using an `Ipv4InterfaceContainer` object (Figure 10).

Now, we have a point-to-point network constructed with the protocol stack and IP addresses assigned. At this point, the application needs to generate traffic. This process is presented in the following section.

To run the simulation, use the `(simulator..Run global)` function (Figure 11). When this function is called, the system will start searching through the list of events programmed and will execute them.

Finally, the cleaning process must be conducted through the `global (simulator..Destroy)` function (Figure 12).

```
Simulator::Destroy ();
return 0;
}
```

Figure 12. Simulation cleaning process.
(Source: The authors.)

```
OnOffHelper onoff ("ns3::UdpSocketFactory", Address (InetSocketAddress (Ipv4Address::GetAny (), port)));
PacketSinkHelper sink ("ns3::UdpSocketFactory", Address (InetSocketAddress (Ipv4Address::GetAny (), port)));
ApplicationContainer app;
```

Figure 13. Creation of helpers for the `ns-3` and `sin` application.
(Source: The authors.)

To conform to the `ns-3` guidelines, it is necessary to create the file in the scratch directory where it is compiled through the `./waf` command and it is run through `./waf --run scratch0.mian`.

3. Construction of the model via discrete events in "ns-3"

It becomes necessary to create in the `ns-3` simulation some servers capable of producing HoD traffic with equal behavior as the traffic produced by the real server. In addition, we must create a client capable of consuming this service and generating statistics of interest for the model. `ns-3` has an application that generates data flows denominated `ns-3 Application I`.

This application is a traffic generator that follows an `ns-3` pattern. After the application starts to run, the `ns-3` and `ns-3` states alternate. The duration of each of these states is determined by the value of the `ns-3Time` and `ns-3Time` variables. During the `ns-3` state no traffic is generated, while during the `ns-3` state traffic is generated.

The attributes to configure the model are: `bitRate` (the application is in the `ns-3` state), `Facet` (the `ns-3` state sent in the `ns-3` state, Remote address of destination), `ns-3Time` variable used to determine the duration of the `ns-3` state, `ns-3Time` variable used to determine the duration of the `ns-3` state. 5. A total of 5 traffic in bytes, which the application sends, and Protocol to use.

3. The functions obtained, `ns-3` frames, `ns-3`, `ns-3`, and `ns-3` corresponds to the `ns-3` state of the application and the time between frames corresponds to the `ns-3` state.

Figure 13 shows a helper for `ns-3` applications, called `ns-3`. It is in charge of configuring and managing these two applications. The constructor of the helper receives parameters that determine the characteristics of the service. The first parameter defines a socket for transmission under the user data protocol, UDP, RTCP (uses the UDP to transmit multimedia content, and the transmission control protocol, TCP, for control data). The second is already the socket as such; an IP address and a port.

Besides the aforementioned, a sink helper is defined, called `ns-3` (in the helper, to receive the data sent. In addition, this helper's constructor receives the same parameters received by the constructor of the helper of `ns-3` to `ns-3`; a chain of characters specifies in a socket for UDP transmission and the socket as such.

4. With the `ns-3` method, seen in Figure 14, the `ns-3` application helper sets the application's attributes. This method receives two parameters; the first is a chain of characters specifies in the attribute of the application sought to be set or modified, and the second is the attribute as such.

```
onoff.SetAttribute("Remote", AddressValue (InetSocketAddress  
(Ipv4Address (csmaInterfaces.GetAddress(i)), port)));
```

<1> 4. Configuration of the remote attribute for the - n- 3 application.
(source: The authors).

```
onoff.SetAttribute("OffTime",StringValue("ns3::  
LogNormalRandomVariable[Mu=0.4026,Sigma=0.0352]"));  
onoff.SetAttribute("OnTime",StringValue("ns3::  
WeibullRandomVariable[shape=10.2063,Scale=57480.9]"));  
onoff.SetAttribute("MaxBytes",UIntegerValue (10989173));
```

<1> 5. Configuration of the - 3Time, - nTime, and 5 a02es
attributes for the - n- 3 application.
(source: The authors).

```
sink.SetAttribute ("Local", AddressValue (InetSocketAddress  
(Ipv4Address (csmaInterfaces.GetAddress(i)), port));  
app = sink.Install (terminals.Get (i));  
app.Start (Seconds (0.0));  
app = onoff.Install (terminals3.Get (1));  
app.Start (Seconds (1.0));
```

<1> 6. Installation of applications in the nodes.
(source: The authors).

```
sink.SetAttribute ("Local", AddressValue (InetSocketAddress  
(Ipv4Address (csmaInterfaces.GetAddress(i)), port));  
app = sink.Install (terminals.Get (i));  
app.Start (Seconds (0.0));
```

<1> 7. Data reception in clients.
(source: The authors).

The code shown in <1> 5 sets the - 3time, - ntime, and 5 a02es attributes. The first two attributes of the application receives, as parameter through the (setAttribute method, a probability function, as shown in <1> 6. This function is obtained from the characterization of the video components. (or this specific case, the ; olnormal function represents the time bet? een t2se + 3frames from video), ? hile the 4 eibull function represents their size. (or videos! and, , the process is analogous.

4 with the instructions shown in <1> 6, an application is extracted from the application container, the parameters established previously are configured in the - n- 3 applications helper, it is installed in the server node, and the time is set in ? hich the function starts to send data.

For data to be received in the client nodes it is necessary to adhere a sink to an application. <1> 7, the (install method, through its (setAttribute method, can configure the client nodes to receive data. The ; ocal attribute refers to the node ? here the data is received, and the 3rd parameter of the method is a socket. Thereafter, an application is taken from the application container and it is installed in the node it ? ill receive. <1> 8, the time is set, in ? hich the node is ready to receive data.

*. Analysis and results

The statistics obtained through the ns3 monitor application are total values along the simulation. These are:

```
std::cout << " Tx Bytes: " << st.txBytes << std::endl;  
std::cout << " Rx Bytes: " << st.rxBytes << std::endl;  
std::cout << " Tx Packets: " << st.txPackets << std::endl;  
std::cout << " Rx Packets: " << st.rxPackets << std::endl;  
std::cout << " Lost Packets: " << st.lostPackets << std::endl;
```

<1> 8. Configuration of statistics.
(source: The authors).

```
std::cout << " Mean{Delay}: " <<  
(st.delaySum.GetSeconds() / st.rxPackets) << std::endl;  
std::cout << " Throughput: " << st.rxBytes * 8.0 /  
(st.timeLastRxPacket.GetSeconds() - st.timeFirstTxPacket.GetSeconds  
( )) << " Mbps\n";
```

<1> 9. Mean value of delay and throughput.
(source: The authors).

```
Ptr<FlowMonitor> monitor;  
FlowMonitorHelper flowmon_helper;  
flowmon_helper.SetMonitorAttribute("StartTime",  
TimeValue(Seconds(1)));  
monitor = flowmon_helper.InstallAll();
```

<1> 10. Creation of a monitor.
(source: The authors).

bytes transmitted and received, packets transmitted received and lost. <1> 9 shows the configuration of these statistics.

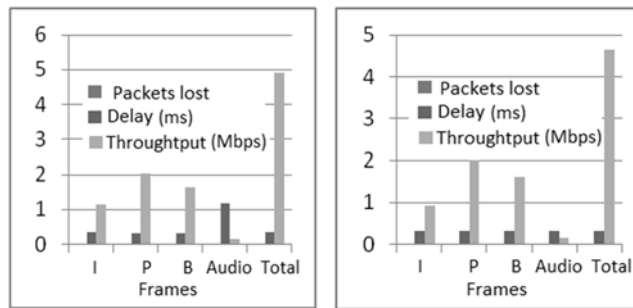
In addition, the delay and throughput as mean value are obtained. <1> 10 shows the configuration of these parameters, ? hile <1> 11 shows the code lines that create the 3rd monitor that must be installed in the net? or previously created.

5.1. Obtaining the throughput

Throughput is obtained by two in three parameters. The first is the time in ? hich the first packet ? as transmitted; the second is the time in ? hich the last packet ? as received; and the third ? as the number of packets received. Two Trace sources <1> 11 ! exist in the net? or device; these are useful to obtain throughput through samples. <1> 12 represents the code used to measure throughput in the net? or <or the first packet through the first packet in the first packet Trace in @ function is called ? henever it is transmitted by the channel; said function registers the time in ? hich it is transmitted. <or the second packet through the second packet Trace in @ function is called each time it is received in the client node. Thus, this function registers the time in ? hich it is received and registers the sum of packets received to that moment in the client node. These two instructions register the throughput, for example, ? ithin a specific node for a client node connected to it.

```
terminalDevices3.Get (1)->TraceConnectWithoutContext  
("PhyTxBegin", MakeCallback (&PrimerPaquete));  
switchDevices3.Get (1)->TraceConnectWithoutContext  
("PhyRxEnd", MakeCallback (&UltimoPaquete));
```

<1> 13. Installation of trace sources.
(source: The authors).



a) Client 1
b) Client 2
Figure 1. Network performance metrics for Client 1 and Client 2. (Source: The authors.)

5.2. Analysis of results for topology 1

Figure 1 shows the results obtained for loss of packets, delay and throughput for each of the two sets of frames of clients 1 and 2 in the simulation (video) over topology 1.

None of the clients had loss of packets. Delay values are 0.1 ms for client 1 and 0.2 ms for client 2. The parameter values of client 1 may be different to clients since these values correspond to an average of multiple simulations, we set the seed different. These values are within the range permitted to offer HoD with Eulit2 of service Uo (according to I) and 4J which specifies a value below 1 ms for a local environment.

Figure 2a shows that throughput between the server and client 1 has a mean of 4.5 bps and Figure 2b shows that throughput between the server and client 2 has a mean of 4.5 bps. Throughput for the link between the server and client 1 is on average of 4.5 bps, as seen in Figure 2.

Tables 3 and 4 contain the results obtained for the network performance parameters from the simulation of each video for topology 1.

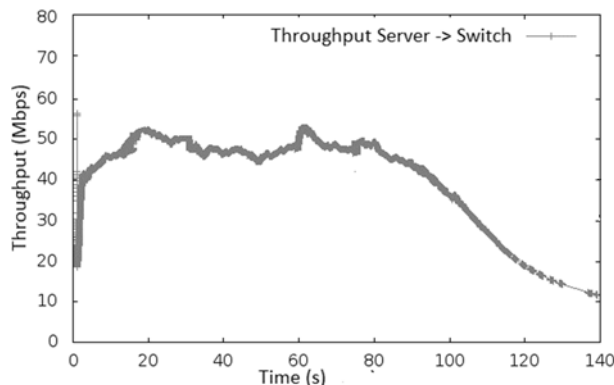


Figure 2. Throughput between server and client. (Source: The authors.)

Table 3
Topology 1, mean delay values for clients 1 and 2

	Video 1	Video 2	Video
Client 1	0.1	0.2	0.15
Client 2	0.2	0.4	0.1

(Source: The authors.)

Table 4
Topology 1, mean throughput values

	Video 1	Video 2	Video
Server & Client 1	4.5	4.5	4.5
Client 1 & Client 2	4.5	4.5	4.5
Client 1 & Client 2	4.5	4.5	4.5

(Source: The authors.)

According to Table 3, and taking as reference the design of network or with end to end service Eulit2 of 4J, the videos under these characteristics comply with the Uo (parameter for the delay).

Observe that with respect to the throughput, the highest value appears for video 1; this may be explained by the delay of precision the FD have with the real traffic, as noted in Table 1; in addition, it may be seen that the necessary transference rate is around 5 bps between the server and the server when all clients simultaneously request video 1. This is an extreme case, which is a network planner with the characteristics of topology 1 and a bandwidth in the order of tenths and above 5 bps is not a high value for current data network or can offer HoD service with Uo.

5.3. Analysis of results for topology 2

Tables 5 and 6 present the results obtained for the network performance parameters, from the simulation of each video for topology 2.

Note that topology 2 also does not have problems regarding delay and its maximum value is below 1 ms. As increase with respect to topology 1 may be explained by the presence of two servers between the server and the end client. With respect to throughput, note that the maximum value is quite close to the value of topology 1; this is because the number of clients is the same and only change the topology. According to the aforementioned, for a network or planner the same concepts emitted for topology 1 are valid.

Table 5
Topology 2, Delay for clients 1, 2, 3, and 4

	Video 1	Video 2	Video
Client 1	0.4	0.4	0.4
Client 2	0.4	0.4	0.4
Client 3	0.4	0.48	0.4
Client 4	0.4	0.4	0.4

(Source: The authors.)

Table 6
Topology 2, mean throughput values

	Video 1	Video 2	Video
Server & Client 1	4.5	4.8	4.5
Client 1 & Client 2	4.5	4.8	4.5
Client 1 & Client 4	4.8	4.5	4.5
Client 1 & Client 3	4.5	4.5	4.5
Client 1 & Client 4	4.5	4.5	4.5

(Source: The authors.)

Table 7.

Topology 12, (scenario), Delay.

	Delay (ms)	
	Video 1	Video 2
Client 1	1.8	1.8
Client 4	1.8	1.8
Client *	1.8	1.8
Client =	1.8	1.8

(Source: The authors).

Table 8.

Topology 12, (scenario), mean throughput values.

	Video 1	Video 2	Video
(Server & Router)	4.8	4.8	4.8
Router 1 & Router 2	1.8	1.8	1.8
(Client 1 & Client 4)	4.8	4.8	4.8
(Client 1 & Client *)	4.8	4.8	4.8
(Client 1 & Client =)	4.8	4.8	4.8

(Source: The authors).

5.4. Analysis of results for topology 3 scenario 1

Tables 7 and 8 display the results obtained for the network performance parameters from the simulation of each video for topology 12, (scenario).

For topology 12, (scenario), it may be noted that the delay increased drastically reaching a maximum value of 1.8 ms; however, it does not exceed the limit stipulated in [1], [4]. This increase can be explained through the increase of intermediate devices between the server and the end client. For its part, throughput is within the values found for topologies and [1].

5.5. Analysis of results for topology 3, scenario 2

The following in shows the results corresponding to the results found for the network performance parameters for the simulation of video 1 over topology 12, (scenario). Figure 4 illustrates the results obtained from loss of packets, delay, and throughput for clients 1 and 4. Note that on this occasion there is a considerable loss of packets for both clients, with 1.8 packets lost for client 1, and 8 packets lost for client 4. The maximum size of the packet is 4080 bytes (the size minus the header of the layer 2, and layer 4 protocol) and bearing in mind the size of the video shown in Table 1, it can

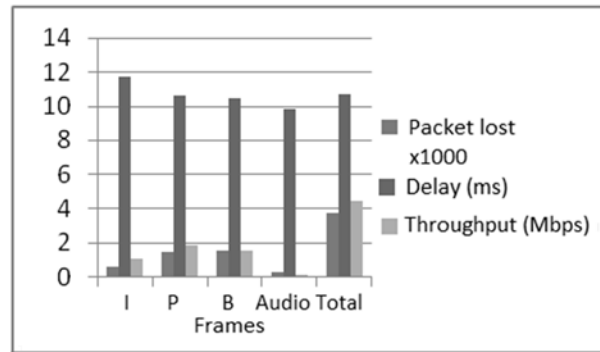


Figure 4b. Packet lost, delay, and throughput for client 4 in topology 12, (scenario). Packet lost, delay, and throughput for clients 1 and 4. (Source: The authors).

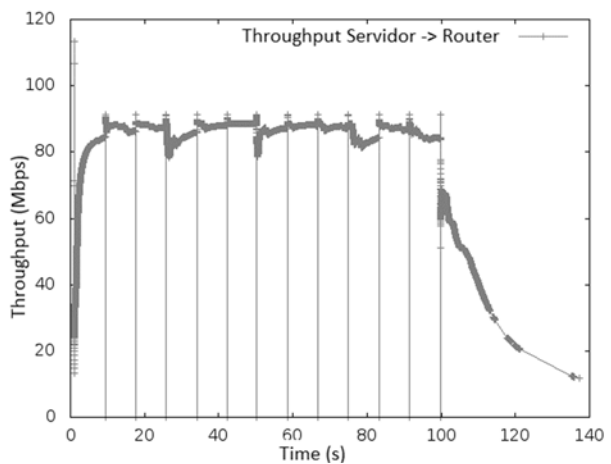


Figure 4a. Throughput between server and router.

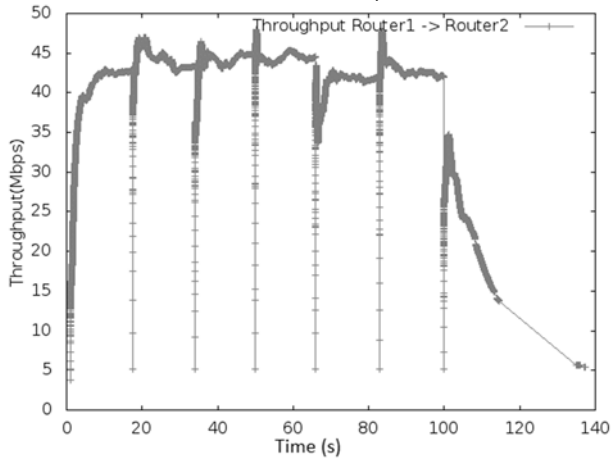


Figure 4b. Throughput between router 1 and router 2 in topology 12, (scenario), throughput. (Source: The authors).

be concluded that loss of packets for client 1 is 1.8%, while for client 4 it is 8.33%; these values are above the 1% accepted for loss of packets in a local area network according to [1], [4].

It is also noted in Figure 4 that the delay is as on average 1.8 ms for client 1, and 1.8 ms for client 4, and throughput

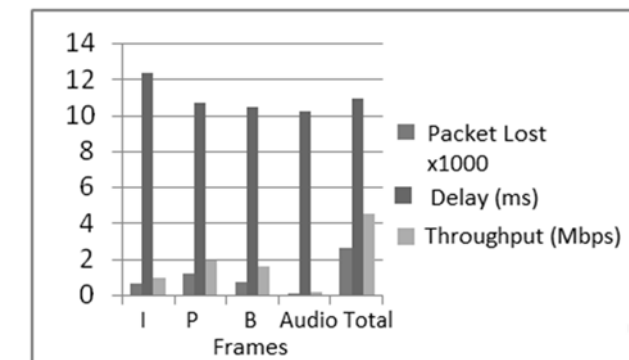


Figure 4a. Packet lost, delay, and throughput for client 1.

Table 1.

ToS12, T (scenario 1, Delay for clients, 4, *, and =).

	+ delay (ms)		
	Video 1	Video 2	Video
Client, Router	8=	8=	8=
Client 4	44.4	4%	1%
Client *	4%	4%	1%
Client =	4%	4%	1%

(Source: The authors).

Table 2.

ToS12, T (scenario 1, 5 throughput values).

	Throughput (bps)		
	Video 1	Video 2	Video
Server & Router	8=	8=	8=
Router & Router	44.4	4%	1%
(? itch, & Client	4%	4%	1%
(? itch, & Client4	4%	4%	1%
(? itch, & Client*	4%	4%	1%
(? itch, & Client=	4%	4%	1%

(Source: The authors).

as a \$ro0imatel 2 4.5 b/s for client, and 4.1 5 b/s for client 4. Also, as observed in <1.1%a, throughputs as a \$ro0imatel 2 8= 5 b/s for the lin@bet? een server and router), and 44.4 5 b/s bet? een router) and router!, as noted in <1.1%b.

4. With respect to the delay, it is observed that this toS12 comes with the Uo(parameters specified in I), 4J. Throughputs presents a maximum value and reaches a value of 8= 8.5 b/s; this is an extreme case, which is? h2 a net? or @ \$lanner? ith the characteristics of toS12, scenario 1? ill require a bandwidth around = 5 b/s, which is not a high value for current local area data net? or @. 9. However, under these conditions, Uo(cannot be guaranteed due to the loss of packets exceeding the maximum permitted.

Tables = and)" present the results obtained for the net? or @ performance parameters from the simulation of each video for toS12, scenario 1.

.. Conclusions

The model described in this article permits replication and reconstruction, according to the toS12 desired and the various characteristics of the services requested. <or e0amle, is a net? or @ \$lanner? ishes to provide the HoD service? ith Uo(to users? ith conditions similar to those described in toS12, scenario 1, it? ill be necessary to see@ alternatives, li@ increasing bandwidth or using mirror servers.

5. Measurement of net? or @ performance parameters, li@ throughput and delay, is important in the \$lanning and implementation of net? or @, given that these indicate how? ell the net? or @ is? or @n1? ith the load it must support, in addition to being important parameters for Uo(.

The processing level of each toS12 influenced upon the performance delay parameter, showing that inasmuch as the toS12s become more complex, the value of said parameter also increases.

Note that the net? or @ parameters measured bet? een the server and the first device to which it is connected, and

bet? een a server and a client, remain constant in the site of the channel of the toS12s, which permits verification of these do not influence upon these links.

The delay values in the toS12s) and 1 remained below a millisecond. The toS12 showed a delay increase caused mainly by adding routers and links bet? een these, besides the delays of the links bet? een the routers and the processing of the packets in each of the net? or @ devices.

ToS12, scenario 1 displayed a percentage loss of packets above 4% of the total and the delay value exceeds 1" milliseconds. In conclusion, toS12, scenario 1 is not capable of supporting simultaneous consumption of the videos.

; loss of packets occurred because the queue size that devices can support in ns& is insignificant; thus, it is necessary to manage or bear in mind the buffer size in real devices. Net? or @ equipment have buffers that store much information in the queue to prevent loss of packets; the size of these buffers can vary according to the model or brand of the net? or @ equipment and can even be configured.

It is proposed as future work the validation of the results through the development of the experiments in other simulation tools such as - 5 NetLL or - FN8T 5 model as tools capable of supporting the video service model in 1.

Ac/nowledgment

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Crude oil removal from production water using nano-intermediates of a) i- functionalized with malnetic nanoarticles

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Abstract

This work aims to develop nano-intermediates adsorbents based on micrometric silica functionalized with malnetic nanoarticles with high efficiencies in the oil removal, additional to high catalytic activities in the decomposition of the crude oil adsorbed. Silica with sizes 100-200 nm were functionalized with 4-aminobenzene malnetic nanoarticles. The efficiency of the adsorbents was evaluated through batch adsorption experiments of oil from oil in water emulsions at different pH, salinity and oil concentration using a UV-vis spectrophotometer. Results showed that for both the functionalized and the synthesized nano-intermediate, the adsorption equilibrium was reached in less than 10 min. A comparison was made between a material typically used in the oil and gas industry. After the adsorption process, the materials can be recovered and regenerated through thermal processes. It was observed that the malnetic nanoarticles over the functionalized act as a catalyst for decomposition of the adsorbed oil.

Keywords: Production water; Adsorption; Nano-intermediates; Silica; Emulsions; Oxidation.

Remoción de hidrocarburos de aguas de producción de la industria petrolera utilizando nanointermedios como sustratos para funcionalizados con nanoartículos malneticos

Resumen

El principal objetivo de este trabajo es desarrollar nanointermedios como sustratos para un soporte micrométrico de funcionalizado con nanoartículos malneticos para la adsorción de hidrocarburos emulsionados en agua. Se utilizó con tamaño 100-200 nm de sílice funcionalizada con nanoartículos de malnetita de 100 nm en una relación de 8:1. La eficiencia del nanointermedio fue evaluada mediante experimentos de adsorción para lotes bajo diferentes condiciones de temperatura, pH, salinidad y concentración de crudo. Tanto para el soporte de funcionalizado como para el nanointermedio, la cantidad máxima de adsorción se alcanzó a los 10 minutos. Las capacidades adsorptivas del nanointermedio fueron comparadas utilizando un material comúnmente empleado en la industria petrolera. Adicionalmente, los materiales pueden ser regenerados mediante procesos térmicos para su posterior reutilización. Se observó que la inclusión de los nanoartículos de malnetita al soporte de funcionalizado genera un efecto catalítico en la descomposición de los hidrocarburos adsorbidos.

Palabras clave: Agua de producción; Adsorción; Nanointermedio; Tratamiento; Floculación; Oxidación.

1. Introducción

La producción de petróleo en Colombia tiene como consecuencia una gran cantidad de agua producida, la cual trae

en ella diferentes elementos tóxicos. Actualmente las aguas producidas en los campos petroleros traen consigo varios problemas asociados a las que pueden llegar a su superficie emulsionadas con petróleo. Más de 20 otros componentes

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nocivos \$ara el medio ambiente. J as em\$resas o\$eradoras deben di\$oner adecuadamente de estas aluas \$ara cum\$lr con las normas ambientales eoiidas 2a sea en re'in2eccDn en los 2acimientos \$ara tener un ma2or recobro o di\$onerlas en \$uentes h2dricas cercanas. Estas di\$osiciones 3nales del alua \$roducida re\$resentan altos costos en las o\$eraciones de \$roducciDn \$ara las em\$resas N*Q \$or lo Cue se ha hecho un es3uer5o constante \$ara encontrar alternativas econDmicamente viables e innovadoras \$ara el mane@ de esta \$roblemtica.

En la etapa de \$roducci3n de cualCuer cam\$3o \$etrolero el \$uido Cue se \$roduce \$uede ser una mezcla de varios com\$onentes incluidos el \$etrdio, alua, las 2/o materiales \$didos como \$artculas sus\$endidas, sales disueltas, metales \$esados 2/o elementos radioactivos, etc. NO Fs un claro com\$3o la \$roducci3n de alua en el cam\$3o Castilla ubicado en los llanos orientales de Colombia, donde se es\$era Cue \$or *("" "" barriles de crudo e3traido se \$roduscan alrededor de 4 millones de barriles de alua NO Ante esto, e3iste la necesidad de reali\$ar la se\$araci3n adecuada en su\$erficie en aras de aumentar el valor comercial del crudo \$roducido 2 mitilar \$osibles \$problemas ambientales asociados. Jos tratamientos reali\$ados a las aluas de \$roducci3n des\$u\$ de la se1re1aci3n en se\$aradores a nivel de cam\$3o, inclu2en \$ases secundarias 2 terciarias. Ja eta\$a secundaria inclu2e \$procesos de \$otaci3n de las +P9 \$or las silas en in1\$ de +nduced Pas9lotation#14, 807 ara esto se utili\$an tanCues de +P9 Cue \$ermiten la entrada de un 1as determinado al \$uido a tratar 2 cu2as burbu\$as se adhieren 2 \$otan con el crudo Cue desea removerse NO En cuanto a la eta\$a terciaria se destacan las tecnolog1as de o3idaci3n avanzada NO membranas N'""Q 2 adsorci3n N""*40) in embar1o, este ti\$3o de tratamientos \$ueden tener una alta relaci3n costo/beneficio de\$endiendo los reCuerimientos de \$ure\$a de los \$uidos \$roducidos 2 aunCue e3isten varios trabajos sobre esta \$problemkica aLn es di\$icil encontrar un \$proceso altamente costo' e\$ectivo. Jos \$procesos adsoritivos son los mks utili\$ados debido a su sencille\$ 2 ba\$a relaci3n costo/beneficio N*",*4,*80) e tiene el uso de materiales como carb3n activado, cascarilla de nue\$, arcillas, co' \$olm3eros, \$eolitas 2 resinas N*,*4,*%0 como los mks utili\$ados. Ja cascarilla de nue\$ es un \$producto del \$proceso de molienda Cue se reali\$a al \$ruto de la \$alma de coco o a\$ricana. Fste \$producto sin nin1Ln ti\$3o de tratamiento o adici3n de Cu3micos ha \$resentado ca\$acidades de remoci3n de crudo en \$lantas de \$iltraci3n del orden de 1""11A debido a sus ca\$acidades oleo\$icas \$re\$erencia hacia el crudo#. Ademks debido a su di\$ponibilidad 2 ba\$a costo re\$presenta unos de los materiales mks usados en lechos \$3os \$ara remoci3n de crudo 2 aceites de 1randes vol\$menes de \$uido N""0

Aunque los materiales micrométricos presentan buenas características adsorptivas, la nanotecnología ha ganado la atención de los inversores debido a las propiedades excepcionales que desarrollan los materiales a esta escala. El diminuto tamaño de las nanopartículas, entre 10^{-9} a 10^{-7} nanómetros hace posible que tengan una alta relación área superficial/volumen que sumado con su naturaleza química permite su aplicación en distintas áreas como almacenamiento, producción y conversión de energía (1).

IQ 2 tratamiento de aguas N°1, !, !!! & O En la industria del Sotrdeo se ha visto 1ran \$otencial de la nanotecnol1a en la remociDn de Sotrdeo de aguas de \$roducciDn N°, !, !, !, ! %

Pu et al. N (Q em\$learon nanocom\$uestos de \$ol\$meros ma\$nticos e hidro3bicos \$ara la remoci3n de aceite de su\$erficies de alu\$. Jos materiales utilizados mostraron alta eficiencia en la adsorci3n de tres tipos de aceites con capacidades adsorptivas de incluso , veces el \$eso del adsorbente 2 Cue adem\$ \$ueden ser sencillamente recolectadas mediante la inducci3n de un cam\$o ma\$ntico e3terno.

Jas nano\$artículas de sílice con \$ro\$iedades como buena estabilidad química, baja densidad, baja toxicidad y mayor área superficial, se presentan también como buenas candidatas para la remoción de hidrocarburos (N8,110) (2ed et al. N"Q observaron el comportamiento del potencial adsorbtivo de una nano-silica hidrofóbica Aerosil R8*1 con tamaño de (nm) en el tratamiento de agua contaminada con gasolina y diesel. Este nanomaterial presenta eficiencias de remoción alrededor del 100%. Los estudios cinéticos indicaron que el 100% de la gasolina es removida después de 5 minutos de contacto. El porcentaje removido del contaminante fue linealmente dependiente de la masa del adsorbente. Recientemente, se ha desarrollado un exhaustivo trabajo en el entendimiento del proceso de adsorción de crudo fuertemente emulsionado en agua usando nano\$artículas de alúmina y sílice funcionalizadas con residuo de refinación (N"40) y encontraron que la funcionalización de las nano\$artículas con el residuo de refinación incrementa la hidrofobicidad del material y permite la adsorción selectiva del crudo con porcentajes de hasta 100% de remoción (N"40). Adicionalmente, se observó que los nanomateriales utilizados presentan altas capacidades adsorbtivas en ambientes con diferentes temperaturas, pH, concentración de crudo emulsionado, salinidad y dosificación de adsorbente. Sin embargo, el pequeño tamaño de las partículas puede generar problemas a la hora de aplicación a escala industrial debido a altas diferencias de presión que se pueden generar en las columnas adsorbtivas en operaciones a nivel de campo, por lo que un material de mayor tamaño que posea propiedades similares a las de las nano\$artículas se presenta como una excelente opción para este tipo de aplicaciones. En el caso de los nanointermedios, los cuales se caracterizan por tener un tamaño micrométrico, que pueden incluir nanomateriales y tomar sus ventajas funcionales y que se prevé tendrán una aplicación directa en el ámbito industrial. El uso de nano\$artículas marplatenses permite su implementación tanto a nivel de campo como en circunstancias de derrames petroleros en diferentes tipos de fuentes hídricas. En el caso de su implementación a nivel de campo, las nano\$artículas de marplatense pueden ser regeneradas y reutilizadas después del proceso adsorbtivo debido a sus propiedades catalíticas frente a la descomposición de hidrocarburos pesados. En este sentido, Nassar et al. (N"40) encontraron que nano\$artículas de marplatense tienen una alta afinidad hacia la adsorción de hidrocarburos pesados, en adición a la reducción en la temperatura necesaria para iniciar su descomposición en procesos oxidativos. Adicionalmente, como valor añadido y debido a sus propiedades marplatenses, en el caso de derrames

Setroleros las nano\$artículas ma1n<ticas \$ueden ca\$urar el crudo 2 des\$u<s ser recu\$eradas mediante la inducciDn de un cam\$o ma1n<tico N! O) in embar1o, hasta el momento no se ha re\$ortado nin1Ln estudio Que utilice nanointermedios \$ara este ti\$o de a\$licaciones. 7or ende, este traba\$ \$ro\$ende al desarrollo 2 evaluaciDn de nanointermedios utili\$ando \$artículas microm<tricas de)i-; como so\$orte 2 nano\$artículas ma1n<ticas como material 3uncionali\$antes \$ara la remociDn de hidrocarburos de a1uas de \$roducciDn.)e \$retende Que el desarrollo de un nanointermedio con caracteri\$icas catali\$icas \$ro\$orcionadas \$or las nano\$artículas de ma1netita \$ermita su recu\$eraciDn/re1eneraciDn \$ara a\$licaciDn a escala de cam\$o.)e e\$e\$ra Que este estudio abra un me\$or \$anorama acerca de la a\$licaciDn de la nanotecnolo1a en la industria \$etrolera con miras a un \$osible desarrollo a escala \$iloto Que \$ermita o\$timizar o\$eraciones de \$roducciDn 2 1enere un im\$acto \$ositivo en el medio ambiente.

2. Materiales

Crudo liviano colombiano con una 1ravedad A7+de , Q a1ua desioni\$ada 2 RCI II.&A, A; C Jaboratorios, Colombia#, 3ueron utili\$ados \$ara la \$re\$araciDn de emulsiones de crudo en a1ua - /M#. El crudo utili\$ado tiene un contenido de saturados, arom<ticos, resinas 2 as<altenos de 4, 8", , *.(!,!!., , 2!.*&A \$/\$, res\$ectivamente. BN- , %&A\$/\$, CARJ- FR; A Reacti\$'D), #alia# 2 Na- B 8"A,)i1ma Aldrich, U)A# 3ueron utili\$ados \$ara la modi\$icaciDn del \$B del sistema. El material de so\$orte evaluado 3ue \$lice)i-; #suministrado \$or)umicol)A.). Colombia# el material 3uncionali\$ante 3ue ma1netita de tama\$ nano\$artitulado Nanostructured : Amor\$ous = aterials, Bouston, TS# 7ara el \$retratamiento de la \$lice 2 la 3uncionali\$aciDn con las nano\$artículas de ma1netita se utili\$DNB4- B , "A,)i1ma Aldrich, U)A#2 etanol)i1ma Aldrich, U)A#. Adicionalmente, en las \$ruebas de adsorciDn \$or lotes se utili\$D un material comLnmente usado en la industria \$etrolera como la cascarilla de nue5 ; a4er, Colombia# con 3nes com\$arativos.

3. Metodología

3.1. Caracterización de materiales

El so\$orte de)i-; , las nano\$artículas de ma1netita 2 el nanointermedio 3ueron caracteri\$ados \$or adsorciDn de N₂ a '1% 2 microscopía electri\$ica de barrido)F= \$or sus si1las en in1l<s#. J as isotermas de adsorciDn de nitrDeno 3ueron obtenidos con un Autosorb'*. Tuantacrome# 2 los valores de Krea su\$erficial); FT# calculados usando el modelo de ;runauer, Fmmet 2 Teller N₂, , 40 J as micro1ra3as 3ueron tomadas con un microscopio electri\$ico 6) = '%41"J8 6F- J, U)A#.

3.2. Preparación de los nanointermedios

J as \$artículas de \$lice se 3uncionali\$aron con nano\$artículas de ma1netita en una relaciDn de &A \$/\$. 7rimero, la \$lice se seca a *!" 2 durante ! h \$ara eliminar

cualquier humedad.)e reali\$a un \$retratamiento del so\$orte en una soluciDn acuosa con NB4- B 2 etanol en relaciones de 8.&A 2 4% v/v, res\$ectivamente. El \$retratamiento se reali\$a ba\$ alitaciDn a *&' r\$m durante * hora 2 a !& 2 \$ara una relaciDn de 4 mJ de soluciDn \$or cada 1ramo de material N&O 7osteriormente, se alre1a la ma1netita nano\$articulada \$ara do\$ar el so\$orte 2 se de\$a alitar \$or 4 horas m&s ba\$ las mismas condiciones de alitaciDn 2 tem\$eratura. Al 3inalizar el \$eriodo de alitaciDn, se calienta la sus\$ensiDn a *&' 2 \$ara eva\$orar la soluciDn acuosa. 7eridicamente se alre1a etanol como alente de lim\$ie5a, ase1urando Que el material Cuede libre de NB4- B. 9inalmente, el material 3uncionali\$ado es secado de nuevo durante ! horas a *!" 2 \$ara \$oder eliminar humedad remanente del \$roceso de 3uncionali\$aciDn.

3.3. Preparación de las emulsiones

J as emulsiones de crudo en a1ua se \$re\$araron me\$clando ambos com\$onentes a *% r\$m durante ! minutos. J a salmuera se \$re\$arD me\$clando RCI 2 a1ua desioni\$ada a %" r\$m, \$ara alcan\$ar una concentraciDn de &' m1/J. J as emulsiones neutras se llevaron a condiciones 1cidas 2 b&sicas adicionando al1cuotas es\$e&icas de BN- , al ".* N 2 Na- B al ".* N, res\$ectivamente.)e ase1urD la estabilidad de las emulsiones monitoreando cada ! 4 horas el cambio en el tama\$ de la 1ota del aceite usando un microscopio D\$tico R7J, ; = icroscopos +ND+A, +ndia# 2 la absorbancia utili\$ando un F\$ectro3otDmetro U8'8 is Penes2s *) Thermo cienti\$ic, Estados Unidos#N*, *! O

3.4. Experimentos de adsorción por lotes

J os e\$erimentos de adsorciDn \$or lotes se reali\$aron mediante colorimetría N! , %Oa di\$erentes tem\$eraturas de ! & , &2 4& 2 a di\$erentes concentraciones iniciales !, # de crudo en salmuera de entre " 2 &' m1/J.)e reali\$D una curva de calibraciDn de absorbancia en 3unciDn de la concentraciDn de crudo, utili\$ando emulsiones a di\$erentes concentraciones conocidas de crudo en a1ua con un es\$ectro3otDmetro Penes2s *) Thermo)cienti\$ic, Malham, = A# a una lon1itud de onda 3a de , " nm con una incertidumbre de ".** a.u., o Que im\$lica una desviaciDn de ".& m1/J en la concentraciDn medida.)e utili\$5a una relaciDn M #de volumen de soluciDn 2 \$eso seco de adsorbente de * 1/J N% J as muestras se alitan a !" r\$m \$or ! 4 horas \$ara ase1urar el eCuilibrio de adsorciDn, tomando al1cuotas cada & minutos. 9inalmente, el nanointermedio con el crudo adsorbido es retirado de la soluciDn mediante centri3u1aciDn \$or & min a 4" r\$m utili\$ando una centri3u1a Bermle U, "% J abnet, Fdison, N6#. 9inalmente, la cantidad adsorbida ads# en unidades de m1/1 se determina mediante el si1uiente balance.

$$q_{ads} = \frac{I_i - I_f}{M} \quad \text{**}$$

donde I_i es la concentraciDn de \$etrDleo en el sobrenadante medida en el eCuilibrio. J os e\$erimentos se

reali\$aron \$or tri\$licado 2 el error re\$resentado en 3orma de barras 3ue calculado mediante el m<todo de) chult\$ 2 Cole N (, , 80

3.5. Análisis termogravimétricos

J os \$procesos de descom\$osiciDn del crudo adsorbido en el nanointermedio se reali\$aron ba@ atmD\$3eras oóidantes e inertes utilizando aire seco 2 nitrógeno, res\$ectivamente.) e seleccionaron la muestras con un valor 3@ de $ads V \text{ " ! } m^1/m^1$ \$ara 3ines com\$arativos 2 manteniendo un \$eso inicial ba@ cercano a los & m1 \$ara evitar limitaciones di\$usionales NIO J os análisis termogravimétricos se llevaron a cabo utilizando una termobalan\$a T & ' TA instruments, inc., Ne4 Castle, DF# ba@ 3u@ constante de $^{***} mJ/min$ del res\$ectivo 1as. 7revio al inicio de los análisis, las muestras son secadas a $^{***} ^\circ C$ durante %h en una estu\$za \$ara remover cualquier humedad. J os análisis se reali\$aron \$or tri\$licado \$ara una tasa de calentamiento 3@ de $^{**} ^\circ C/min$ entre , " 2 $8^{***} ^\circ C$, \$ara el crudo adsorbido 2 \$ara la muestra \$revia a la adsorciDn. J a actividad catalítica del nanointermedio se evaluarK mediante el \$orcentaje de conversiDn a determinada temperatura de la si l uiente manera.

$$\text{conversión} = \frac{m_i - m_f}{m_i - m_f} \times 100\% \quad ! \#$$

donde m_i , m_f 2 m_i son la masa de muestra al \$rincipio de la \$rueba, al 3inal de la \$rueba 2 a determinado tiempo t , res\$ectivamente.

4. Modelos adsorptivos

4.1. ! odelo do"le exponencial

El modelo doble eó\$onencial es utilizado \$ara describir el com\$ortamiento de la cantidad adsorbida en 3unciDn del tiempo de contacto. El modelo da cuenta del \$proceso adsorptivo teniendo en cuenta un \$eriodo de adsorciDn rK\$ida 2 un \$eriodo lento. J a ecuaciDn que describe el modelo doble eó\$onencial es la si l uiente M" , 4*O

$$ads_t = ads_{max} - \frac{Q_1}{M} e^{-k_1 t} - \frac{Q_2}{M} e^{-k_2 t} \quad , \#$$

donde ads_t m^1/m^1 es la cantidad adsorbida \$ara uno determinado tiempo t min#. Asimismo, k_1 min^{-1} 2 k_2 min^{-1} , asE como Q_1 m^1/m^1 2 Q_2 m^1/m^1 , son las

constantes cin<ticas de adsorciDn 2 los coeficientes de adsorciDn \$ara los \$asos lento 2 rK\$ido, res\$ectivamente M! O

4.2. ! odelo de \$runauer'Emmet'Teller

El modelo de \$runauer'Emmet'Teller ; FT#M, , 44O describe el 3enDmeno de adsorciDn mediante \$procesos multicapa 2/o monocapa \$ara sistemas l iquido' s lido

mediante las constantes de eQuilibrio $+_s J/m^1 \# 2 +_l J/m^1 \#$, res\$ectivamente M4O

$$ads = ads_{max} \frac{+_s!}{*_+!_+ + *_+!_+ + +_s!_+} \quad 4\#$$

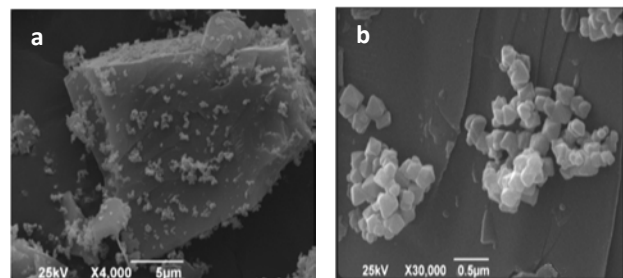
con ads_{max} m^1/m^1 como la capacidad mKóima de adsorciDn.

5. Resultados

5.1. Caracterización de materiales

J a e\$ficiencia del \$proceso de 3uncionali\$aciDn 3ue ma2or al I " A 2 3ue corroborada mediante 1ravimetría. El so\$orte de) i- , las nano\$artículas de ma l netita 2 el nanointermedio sinteti\$ado 3ueron caracteri\$ados mediante adsorciDn de N_2 2 microscopía electrónica de barrido. En la Tabla * se \$resentan los resultados de tamao \$romedio de \$artícula D\$ Krea su\$er3icial \$ara los materiales evaluados 2 en la 9i1. * se \$resentan las imKenes) F= del nanointermedio obtenido \$ara aumentos de $a\# S 4^{***} 2 b\# S, ^{****}$.

En la 9i1. * se observa que las nano\$artículas tienden a al l omerarse sobre la su\$er3icie de las \$artículas de) i- , una ve\$ reali\$ado el \$proceso de 3uncionali\$aciDn, con tamaos \$romedio de alre l ado de a\$roóimadamente ! @n.) in embar1o, se observa una buena di\$ersiDn del material nanom<trico sobre la su\$er3icie del so\$orte. Adicionalmente, en la Tabla * se \$uede observar que el Krea su\$er3icial del nanointermedio aumenta en com\$araciDn con el so\$orte de) i- , debido a la \$resencia de las nano\$artículas de ma l netita en el sistema.



9i1ura *. ImKenes) F= del nanointermedio obtenido \$ara aumentos de $a\# W^{****} 2 b\# W^{****}$.
9uente: FlaboraciDn \$ro\$ia.

Tabla *. Xrea su\$er3icial) ; FT#2 tamao \$romedio de \$artícula D\$ del so\$orte de) i- , de las nano\$artículas de ma l netita 2 del nanointermedio con &A \$/\$ de nano\$artículas de ma l netita.

Material	! " \$ % & 1 m^2/g	() &
! o) rte de ! i* 2	4.*	I (! Y " . * nm
+ ano) rtículas de , e3* 4	* " ! !	* % & Y " . * Zm
+ anointermedio	%!	'

9uente: FlaboraciDn \$ro\$ia.

5.2. Cin ticas de adsorción

La cantidad adsorbida se registró en función del tiempo para el nanointermedio 2 para cada uno de sus componentes por separado, a una temperatura de 25 °C a un valor de B/V (En la Fig. 1 se presentan las cinéticas de adsorción de crudo en el soporte de $i-1$, b# las nanopartículas de $9e-4$ 2 c# el nanointermedio para concentraciones iniciales de 10^{-3} , 10^{-2} y 10^{-1} m1/J.) y se observa que en todos los casos la cantidad adsorbida aumenta a medida que la concentración inicial de crudo aumenta. En general, el tiempo que demora el sistema para alcanzar el equilibrio depende de la concentración inicial de crudo en la muestra 2 del tipo de adsorbente 2 aumenta a medida que i aumenta. Para el soporte de $i-1$, la capacidad máxima de adsorción de crudo se alcanza a tiempos de 8, 21 y 30 min para i de 10^{-3} , 10^{-2} y 10^{-1} m1/J, respectivamente. Asimismo, en el caso de las nanopartículas de $9e-4$, los tiempos requeridos por el material para alcanzar el equilibrio de adsorción se encuentran a 2, 8 y 28 minutos, respectivamente. En el caso del nanointermedio, se observa que para i de 10^{-3} 2 10^{-1} m1/J, la cantidad máxima adsorbida se alcanza al mismo tiempo que en el caso de las nanopartículas de malnetita 2 en embarlo, para el caso de i V & " m1/J el equilibrio se logra a los 5 min, lo que indica que el tiempo requerido por el material híbrido es reducido en aproximadamente 1/2, 1/3, 1/4 en comparación con las nanopartículas de $9e-4$ 2 el soporte de $i-1$, respectivamente. Estos resultados son de gran importancia debido a que en una potencial aplicación a escala de campo, los tiempos de retención pueden ser drásticamente disminuidos mediante el uso de los nanointermedios.

El modelo doble exponencial fue empleado para describir las cinéticas de adsorción de crudo en el nanointermedio 2 cada uno de sus componentes. En la Tabla 1 se presentan los parámetros obtenidos del modelo doble exponencial para las cinéticas de adsorción mostradas anteriormente (Fig. 1) y se observa que el modelo representa adecuadamente los datos experimentales con valores de R^2 [0.982 0.999]. Los resultados indican que el proceso inicia rápidamente mediante la difusión del adsorbato sobre la superficie del adsorbente 2 es seguido por un proceso gradual en el cual el adsorbato alcanza los sitios activos en la superficie del adsorbente N^* , N^*O .

Tabla 1.

Parámetros estimados para el modelo doble exponencial para la adsorción de crudo en el soporte de $i-1$, las nanopartículas de malnetita 2 el nanointermedio para concentraciones iniciales de 10^{-3} , 10^{-2} y 10^{-1} m1/J a 25 °C.

Muestra	i m1/J #	ads, $m1/J$ #	k_f m1/J #	k_d min ⁻¹ #	k_s m1/J #	k_{ss} min ⁻¹ #	R^2	OSM- A
Soporte $i-1$	10^{-3}	4.1	1.11	0.8	1.11	0.04	0.98	1.1
	10^{-2}	8.8	1.11	0.8	4.1	0.01	0.98	4.1
	10^{-1}	18.1	1.11	0.8	4.8	0.01	0.98	4.41
+ nanopartículas, $9e-4$	10^{-3}	8.11	0.11	0.4	8.1	0.01	0.98	1.4
	10^{-2}	14.9	0.11	0.4	11.0	0.01	0.98	8.8
	10^{-1}	18.1	0.11	0.4	18.1	0.01	0.98	1.4
+ nanointermedio	10^{-3}	1.18	1.11	0.88	8.1	0.01	0.98	1.1
	10^{-2}	1.11	1.11	0.88	1.18	0.01	0.98	1.1
	10^{-1}	4.84	1.11	0.88	11.0	0.01	0.98	1.1

Fuente: Elaboración propia.

5.3. Isotermas de adsorción

Las isotermas de adsorción de crudo se construyeron utilizando el nanointermedio 2 cada uno de sus componentes como adsorbentes. Adicionalmente, se utilizó cascarilla de nuez con fines comparativos para corroborar la eficiencia del nanointermedio sintetizado. Se evaluó el efecto del tipo de adsorbente, temperatura, B/V y salinidad.

5.3.1. Efecto del tipo de adsorbente

En la Fig. 1, se presentan las isotermas de adsorción tanto con el modelo de FT para el soporte de $i-1$ 2 cascarilla de nuez, 2 b# nanopartículas de $9e-4$ 2 nanointermedio, obtenidas a 25 °C para un B/V () y se observa que para el caso del soporte de $i-1$, las nanopartículas de $9e-4$ 2 el nanointermedio, las isotermas de adsorción siguen un comportamiento tipo II según la clasificación de la International Union of Pure and Applied Chemistry (IUPAC). Estas isotermas son características de sistemas con alta afinidad en la fase adsorbato \ adsorbente 2 que además muestran un proceso de adsorción multicausa para concentraciones elevadas.

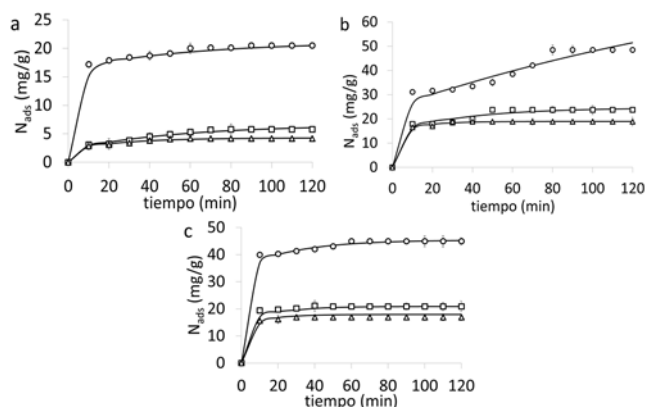


Figura 1. Cinéticas de adsorción de crudo en a# soporte de $i-1$, b# nanopartículas de malnetita 2 c# nanointermedio para concentraciones iniciales de 10^{-3} , 10^{-2} y 10^{-1} m1/J a 25 °C. Los marcadores son los datos experimentales 2 la línea continua representa el modelo doble exponencial.

Fuente: Elaboración propia.

En el caso de la isoterma de adsorción para la cascarilla de nuez, esta presenta un comportamiento tipo L4 con características de sistemas con alta afinidad y con un comportamiento monolítico. En la Fig. 1, se observa que, para todo el rango de concentraciones evaluado, la cantidad adsorbida aumenta en el orden nanoesferas de 9×10^{-4} [nanointermedio [sílice de 1×10^{-4} [CN, indicando que la funcionalización de la sílice con las nanoesferas fue efectiva en el incremento de la capacidad adsorptiva del material. Para un valor de 1×10^{-4} m³/J, donde las isotermas de adsorción pueden ser comparadas, se observan valores de q_{ads} de 48, 48, 48 y 48 mg/g, lo que representa una diferencia del 100% entre las nanoesferas de 9×10^{-4} y el nanointermedio, y aumentos en la cantidad adsorbida del 100% y 200% entre el nanointermedio y el sílice de 1×10^{-4} y la cascarilla de nuez, respectivamente. Los altos valores de adsorción de crudo en las nanoesferas pueden explicarse debido a alta área superficial debido a su tamaño nanométrico. Sin embargo, valores cercanos se obtienen con el nanointermedio y puede deberse a la sinergia entre los grupos funcionales presentes en las nanoesferas y en el sílice de 1×10^{-4} que favorezcan la adsorción del crudo a partir de diferentes selectividades. En este sentido, los heterótomos presentes en el crudo tienen un papel importante en el proceso adsorptivo. Generalmente, heterótomos como $-N$, $-O$ y $-S$ pueden encontrarse en compuestos pesados del crudo tales como asfaltenos o resinas (ver Fig. 2). La interacción entre la sílice y el crudo se da primordialmente por el grupo funcional $-OH$ con los grupos hidrofóbicos en los diferentes componentes del crudo. Además, se ha evidenciado que la adsorción mediante grupos funcionales con $-N$ se da generalmente para superficies con un carácter básico y que además lleva a un valor bajo de cantidad adsorbida (Muller y Curtiss et al., 2008). Por lo tanto, la afinidad entre los componentes presentes en el crudo y la sílice puede darse en el orden $Quinolina > Benzol > Benceno > Bencilo > Sirona$. En el caso de las nanoesferas de 9×10^{-4} , Nassar et al. (2010) observaron que la adsorción de compuestos pesados del crudo aumenta a medida que la cantidad de N aumenta, y por el contrario disminuye cuando el peso molecular del componente, la relación B/C y el contenido de azufre aumentan. Sin embargo, los grupos funcionales contenedores de N pueden tener característica ácida o básica como es el caso de la piridina y el pirrol, respectivamente, lo que puede ocasionar que los componentes presentes en el crudo interactúen diferente con la superficie del material. No obstante, el efecto sinérgico entre el sílice y las nanoesferas de malnetita es claro debido a que el valor de q_{ads} para el nanointermedio es mayor que el calculado mediante la suma de los aportes individuales del sílice y el material funcionalizado. Para el caso de 1×10^{-4} m³/J, el valor resultante de q_{ads} mediante la suma de los aportes individuales sería aproximadamente 100 mg/g, lo que representa una diferencia del 100% en comparación con el valor obtenido experimentalmente para el nanointermedio.

En la Tabla 1, se presentan los valores estimados de los parámetros $q_{ads,max}$, K_s y n del modelo; FT, el cual

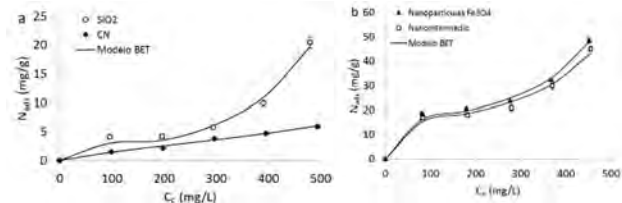


Figura 1. Isotermas de adsorción de crudo en a) sílice de 1×10^{-4} y b) cascarilla de nuez, y c) nanoesferas de malnetita y nanointermedio a 1×10^{-4} m³/J. Los marcadores son los datos experimentales y la línea continua representa el modelo; FT. Fuente: Elaboración propia.

describe de buena manera los datos experimentales de acuerdo a los valores de R^2 [0.98 y 0.99, respectivamente. En general, se observa que $q_{ads,max}$ sigue la tendencia CN [sílice de 1×10^{-4} [nanointermedio [nanoesferas de 9×10^{-4} y está en concordancia con los valores observados experimentalmente. El K_s asociado con la afinidad entre el adsorbato y el adsorbente es específicamente en procesos monolíticos, sigue la tendencia nanoesferas de 9×10^{-4} [nanointermedio [CN [sílice de 1×10^{-4} , indicando que los sistemas en presencia de nanoesferas presentan una mayor afinidad que aquellos en ausencia de las mismas. De manera similar, en el caso del K_s asociado con el n de adsorción multilítica, este sigue la tendencia nanoesferas de 9×10^{-4} [nanointermedio [sílice de 1×10^{-4} [CN. Al comparar los resultados entre el sílice de 1×10^{-4} y CN, y de acuerdo con la forma de las isotermas de adsorción, se observa que la sílice tiene valores más altos de cantidad adsorbida debido a que tiene una tendencia mayor a adsorber el crudo en múltiples en contraste con la CN que favorece un n de adsorción monolítico.

3. Efecto de la temperatura

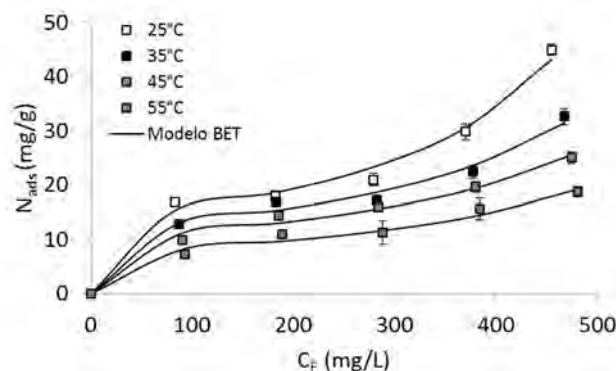
Las isotermas de adsorción se realizaron para el nanointermedio sintetizado a temperaturas de 25, 35 y 45 °C para un valor de 1×10^{-4} m³/J. En la Fig. 2 se presentan las isotermas de adsorción de crudo en el nanointermedio para las diferentes temperaturas evaluadas junto con el ajuste realizado con el modelo; FT. Las isotermas de adsorción presentan un comportamiento tipo L4 y se observa que a valores de 1×10^{-4} m³/J la pendiente de las isotermas de adsorción se reduce a medida que aumenta la temperatura y puede deberse a que se aumenta el n de adsorción tipo monolítico. En general, se observa que la cantidad adsorbida disminuye a medida que aumenta la temperatura del sistema. Para un valor K_s de 1×10^{-4} m³/J, las cantidades adsorbidas son aproximadamente 100, 80 y 60 mg/g para temperaturas de 25, 35 y 45 °C, respectivamente. Los resultados sugieren que la temperatura tiene un efecto significativo en las reacciones de interacción entre el crudo y el nanointermedio y que el proceso de adsorción es de tipo endotérmico. Los resultados están en concordancia con aquellos reportados por

Tabla. .

7 arámetros estimados para el modelo ; FT para la adsorción de crudo en el soporte de) i - , las nanopartículas de malnetita, el nanointermedio 2 cascarilla de nue5. 9uente. Flaboración \$ro\$ia.

Material	) H	\$ em) eratura -./ 0	ads,ma0 'mg(g)	+ _s '*(mg)	+ _l '*(mg)	0 ¹	0SM- A
! o) orte ! i* ₂	(	! &	8.88	*.4(x *''',	*., " x *''',	".18	4.8
+ ano) artículos, e ₃ * ₄	(	! &	*4.**	, &!,	*.8% x *''',	".11	, .8&
	4	! &	8.1 *	%!.!	*.9% x *''',	".11	4.8&
	(	! &	*, .4&	4&8	*.8% x *''',	".11	%!(
+ anointermedio	(	, &	**..84	8'., 4	*., &x *''',	".11	%("
	(	4&	1.14	8%..%	*.11 x *''',	".11	%8"
	(	8&	(., &	8(.8	*.18 x *''', ⁴	".11	8., "
	*''	! &	*&8%	!!.*4	*.8, x *''',	".11	".18
/ ascarilla de nue1	(	! &	4."*	4., 4 x *''',	1.44 x *''', ⁴	".11	%, 8

9uente. Flaboración \$ro\$ia.



9i1ura 4. -isotermas de adsorción de crudo en el nanointermedio a ! & , & 4& 2 &8&C con \$B V(. Jos marcadores son los datos e0\$erimentales 2 la línea continua re\$resenta el modelo ; FT.

9uente. Flaboración \$ro\$ia.

9ranco et al. N**,*! Q Cuienes evaluaron la adsorción de crudo en nanopartículas de almina 3uncionalizadas con residuo de refinera 2 encontraron Que a medida Que la temperatura del sistema aumenta, la cantidad adsorbida disminu2e. Jos \$arkímetros obtenidos del modelo ; FT para la adsorción de crudo en el nanointermedio a diferentes temperaturas se \$resentan en la Tabla ! . En general, se observa Que el modelo \$resenta un buen ajuste 2 Que a medida Que la temperatura del sistema aumenta, los valores de +_s aumentan se \$romueve un \$proceso de adsorción ti\$ó monoca\$ 2 viceversa.

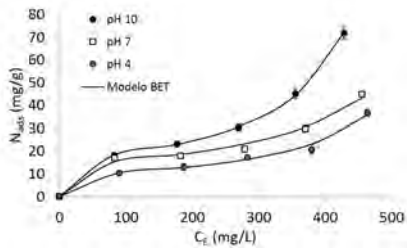
&, ., . Efecto del \$B

El efecto de diferentes valores de \$B de 4 2 *'' 3ue evaluado en la adsorción de crudo en el nanointermedio para una temperatura 3a de ! &C. Jos resultados de las isotermas de adsorción construidas a diferentes valores de \$B son \$resentados en la 9i1. & Cunto con el ajuste obtenido para el modelo ; FT. Jos resultados indican Que el comportamiento de la isoterma de adsorción ti\$ó +-# no se ve afectado \$or cambios en el \$B 2 Que la ca\$acidad adsorptiva aumenta a medida Que aumenta el \$B. Esto se debe a Que diferentes

1ru\$os 3uncionales \$resentes en el crudo tales como carbo0ilo, Cetonas, aldehidos, ben5otio3enos, diben5otio3enos, alquil aril o al-il sul300idos, entre otros, \$ueden sufrir cambios mediante modificaciones en el \$B N**,*! O 7or e0m\$lo, 1ru\$os nitro1enados como \$irrol 2 \$iridia \$ueden encontrarse o no en su 3orma \$rotonada de\$endiendo de su constante de acide5 \$Ra# 2 del \$B del sistema, lo Que directamente afecta su adsorción sobre el nanointermedio. De acuerdo al \$arkímetro +_l del modelo ; FT Tabla ! #, se observa Que el 3enDmeno multiplica\$ toma ma2or im\$ortancia a medida Que incrementa el valor de \$B.

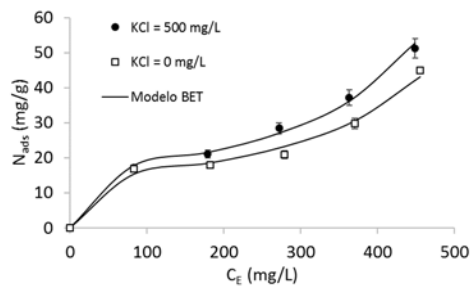
&, .4. Efecto de la salinidad

Ja adsorción de crudo en el nanointermedio se reali5D tambi-n para emulsiones ti\$ó -/M de crudo en alua desionizada 2 de crudo en una salmuera \$re\$arada con 8' " m1/J de RCl. El efecto de la salinidad en el \$proceso adsorptivo es de 1ran im\$ortancia debido a Que 1eneralmente las aluas de \$roducción contienen diferentes sales Que \$ueden afectar la interacción entre el crudo 2 el adsorbente. En la 9i1. %se \$resentan las isotermas de adsorción para ambos sistemas en ausencia 2 \$resencia de RCl a una temperatura de ! &C 2 un \$B V(, Cunto con el ajuste para el modelo ; FT.) e observa Que para todo el rango de concentraciones evaluado, los valores de son ma2ores en \$resencia de RCl. Esto \$uede deberse a Que los iones Cl⁻ actlan de manera re\$ulsiva con aquellos 1ru\$os \$cidos en la su\$erficie del nanointermedio 2 3avorece la a3inidad entre la \$are\$a crudo \ adsorbente. Jos resultados estln en concordancia con lo re\$ortado en estudios \$revious N**,*! Q en donde se evidenciD Que las isotermas de adsorción de crudo en nanopartículas de almina \$resentaban me0res ca\$acidades adsorptivas en \$resencia de una sal. El modelo ; FT se ajustD adecuadamente a los datos e0\$erimentales con valores de 0¹ V ".11 2 0SM- A V , .*1. Jos valores obtenidos para los \$arkímetros ads,ma0¹ +_l 2 +_s 3ueron *&4 m1/1, *.& x *''', J/m1 2 &.8 J/m1, re\$pectivamente.



Se utilizaron tres valores de ΔH de 4, 2 y 1 kJ/mol a una temperatura de 100°C. Los marcadores son los datos experimentales y la línea continua representa el modelo; FT.

9uente. Flaboraci Dn \$ro\$a.



9) Iura % -isotermas de adsorci3n de crudo en el nanointermedio \$ara
di\$erentes concentraciones de RCl a una temperatura de !&C 2 \$ara un \$B
V (. Jos marcadores son los datos e0\$erimentales 2 la l3nea continua
re\$resenta el modelo ; FT.

9uente. FlaboraciDn \$ro\$a.

5.4. Análisis termogravimétricos

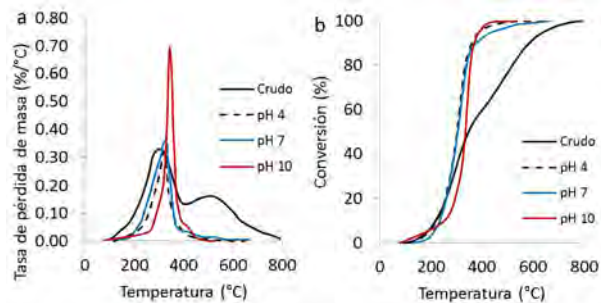
Una de las principales características que debe tener un adsorbente en procesos de remoción de hidrocarburos es su capacidad de regeneración. Por lo tanto, se espera que el nanointermedio sintetizado pueda ser regenerado mediante la desorción del crudo bajo ciertas condiciones de temperatura. Dependiendo del proceso que se siga, los subproductos de la regeneración pueden tener diferentes características. En un proceso de descomposición bajo atmósfera inerte se espera la formación de hidrocarburos livianos que tienen cierto valor añadido. Por otra parte, si la descomposición se realiza mediante un medio menos oxidante, uno de los mayores subproductos esperados es CO₂, el cual podría ser inyectado a condiciones de acimientamiento en procesos de recobro mejorado. Finalmente, para sus aplicaciones en industria.

J a descomposición del crudo \$reviamente adsorbido en el nanointermedio a \$artir de sistemas con diferente valor de \$B se evaluó mediante análisis termogravimétricos bajo atmósferas inertes y oxidantes. Debido a las propiedades del material nanoarticulado, la descomposición del crudo en presencia del nanointermedio es catalizada y ocurre a temperaturas inferiores que para el crudo en ausencia del nanointermedio. En la 9i1. 8 se presentan a# la tasa de pérdida de masa y la conversión para la descomposición del crudo en presencia y ausencia del nanointermedio bajo una atmósfera oxidante. Como se observa en la 9i1. 8a, la tasa de pérdida de masa para el crudo en ausencia de nanointermedio presenta dos máximos alrededor de , "" 2 y 800. El primero se debe a la descomposición de los componentes livianos e intermedios del crudo y el segundo a la fracción más pesada como asfaltenos y resinas. Generalmente, la descomposición inicia mediante el rompimiento de las cadenas alifáticas más cortas y posteriormente de los anillos aromáticos presentes. N. & O

En el caso de los asfaltos 2 las resinas pesadas, estos son compuestos altamente reactivos compuestos por un nucleólo aromático rodeado de cadenas alifáticas 2 que además contienen heterótomos como O , N , S y Cl . A temperaturas bajas, la descomposición de la fracción pesada comienza mediante el rompimiento de las cadenas alifáticas 2 su separación del nucleólo aromático. Posteriormente, se rompen enlaces débiles en el nucleólo lo que podría conllevar a reacciones de adición 2 la formación de compuestos más pesados N_{40} En presencia de las nanopartículas estas reacciones se pueden suprimir. En la 911. (a se observa que

\$ara al descomposici3n del crudo en \$resencia de los nanointermedios se \$resenta un solo \$ico entre , , " 2 , 4" QC \$ara la adsorci3n a \$artir de los sistemas con diferentes \$B. El hecho de Que no se \$resente nin1Ln mK0imo \$a tem\$eraturas[4"" QC indica Que el nanointermedio \$resenta un efecto catal3tico en la descomposici3n del crudo adsorbido. Fsto se corrobora mediante los resultados en la 9i1. (b, donde se observa Que conversiones entre " 2 &' A se lo1ran \$ro0imadamente a las mismas tem\$eraturas en todos los casos, \$ero Que conversiones[&' A reQuieren una ma2or ener11a de activaci3n en el caso del crudo en ausencia de nanointermedio en com\$araci3n con el crudo adsorbido.

En la 9i1. 8 se \$resentan a#la tasa de \$-rdida de masa 2 b#la conversiDn \$ara la descom\$osiciDn del crudo en \$resencia 2 ausencia del nanointermedio ba@ una atmD\$era inerte. De manera similar C ue en el \$roceso de oDidaciDn, se observa C ue la tasa de \$-rdida de masa \$resenta dos m#Oimos en , 4& 2 & 8Q. El aumento en los valores de los m#Oimos \$uede deberse a la \$alta de reactante en el sistema en com\$araciDn con el oDleno en las \$ruebas en \$resencia de aire. 7ara la descom\$osiciDn del crudo en \$resencia del nanointermedio, los resultados muestran C ue se obtiene un solo m#Oimo en la tasa de \$-rdida de masa cerca a los 4''' Q, indicando C ue el efecto catalitico del nanointermedio se obtiene tambi-n ba@ una atmD\$era inerte. Asimismo, en la 9i1. 8b se observa C ue \$ara conversiones ma\$ores a 8' A se re\$uieren ma\$ores tem\$eraturas en ausencia del nanointermedio. Estos resultados son \$romisorios \$ara \$osterores \$plicaciones a nivel de cam\$ C ue \$ermitan la descom\$osiciDn del hidrocarburo a tem\$eraturas ba\$as \$ara el \$roceso de regeneraciDn del adsorbente.



911ura (. #Tasa de \$<rdida de masa 2 b#conversiDn baQ atmDs era o0idante
\$ara la descomposiciDn de crudo \$revio a la adsorciDn 2 crudo adsorbido en
el nanointermedio a \$artir de emulsiones con di3erentes \$B de 4, (2 *".

9uente. FlaboraciDn \$ro\$a.

- (4



A 4 o+5 call classifier for carrier Grade based on) u\$Sort 4 ector 7 achines

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Abstract

Currently, 4 o+5 companies technicians conduct tests to classify call quality as good or bad. Even though, there are automatic platforms that make test 4 o+5 calls to classify them, they do not perform audio processing to detect false Answer) u\$version ? A) #, which is a common and undesirable feature of 4 o+5 calls. In this paper, a 4 ector) u\$Sort 7 achine) 4 7 # along with several functions used in voice recognition were implemented to emulate the human decision procedure the task of audio classification and analysis performed by technicians. The experiments were based on the comparison between the results obtained from the current classification methods and those derived from the) 4 7 . A 10 fold cross validation was used to evaluate the system performance. The test results from the proposed methodology show a better percentage of successful classification compared to a selected automatic platform called Chec7 2Routes.

Keywords- Audio analysis; pattern recognition;) 4 7 ; 4 o+5.

Clasificador de llamadas 4 o+5 para calificar un proveedor basado en) u\$Sort 4 ector 7 achine

Resumen

Actualmente, los técnicos de compañías de 4 o+5 realizan pruebas para clasificar las llamadas como buenas o malas. Asimismo, existen plataformas automáticas que realizan llamadas 4 o+5 para clasificarlas, sin realizar procesamiento de audio; proceso necesario cuando se pretende detectar el false Answer) u\$version ? A) #, una característica común e indeseable de las llamadas 4 o+5. Se implementó una 7 D-quina de 4 ectores de) o\$orte) 4 7 # junto con varias funciones utilizadas en el reconocimiento de voz para emular la toma de decisiones de los humanos tarea de clasificación y análisis de audio realizada por los técnicos. Los experimentos se basaron en la comparación entre los resultados obtenidos de los métodos de clasificación actuales y los derivados de la) 4 7 .) e utilizó una validación cruzada de diez veces para evaluar el rendimiento del sistema. Derivado de los resultados, la metodología propuesta muestra un mejor porcentaje de clasificación exitosa comparado con una plataforma automática llamada Chec7 2Routes.

Palabras clave- Análisis de audio; reconocimiento de patrones;) 4 7 ; 4 o+5.

1. Introduction

Today 4 o+5 calls are part of a larger market in which 4 o+5 carriers conduct interconnection contracts with similar companies so they can complete most of their traffic. The unregulated tariff definition of voice minutes, transferred using 4 o+5, allows their value to be more competitive and really attractive for companies which win the market.

These new companies tend to let attract the customers from traditional ones whose tariffs are regulated. Studies have shown that 4 o+5 traffic continues to grow and the number of carriers offering the service has increased as well. Therefore a large number of companies have emerged offering 4 o+5 destinations at competitive prices.

The technical support department of a 4 o+5 carrier, among other duties, is in charge of testing the destinations



offered b2 the su\$liers o6 the com\$an2. This tas> is \$erformed to determine their suitability to handle 4 o+5 traffic. Accordin0 to the testin0 result, the carrier can decide @hether to sell the destination to its customers. Nevertheless, ta>in0 into account that most o6 the time there is a lar0e <uantit2 o6 offers received from different vendors, it is necessar2 to loo> for the best su\$lier @hose cost' <ualit2 factor the customer @ants a termination that com\$letes 4 o+5 calls @th0ood <ualit2 at a 0ood \$rice# better adGists to the customer's re<uirements.

It should be noted that the destination o6 a su\$lier can be real2 volatile, i.e., there ma2 be offers @hich are @or>in0 0ood durin0 one da2 at ver2 attractive \$rices but then the2 can disa\$sear for a lon0 time. The \$rom\$tness in @hich such offer is 6ound and used, is 6undamental for ta>in0 advanta0e o6 this >ind o6 o\$ortunities so the 4 o+5 traffic can be com\$leted in better economic conditions.

Technicians o6 4 o+5 carriers determine manual2 the classification o6 several 4 o+5 calls in order to decide i6 the su\$lier is suitable for traffic com\$letion. ?irst, the2 anal2Ce the duration o6 5ost Dial Dela2 and Rin0 Time for each call. Then, i6 a call is connected has duration#, the2 determine @hether it has voice or not, listenin0 to the audio that comes from the end user. ?alse Ans@er) u\$ervision calls contain rin0 bac> tones, noise or dead air no audio or environment audio#@hich is char0ed to the end user. ?inal2, based on the anal2sis o6 several calls, the technicians state @hether the su\$lier is a\$ or no a\$ for traffic termination.

There is not a s\$ecific number o6 attempt\$ that needs to be anal2Ced in order to define that a su\$lier @ll have a 0ood or bad \$erformance. Lo@ever, the more number o6 calls, the more the achieved accurac2. ?rom statistics, (" or more attempt\$ are needed to determine a numeric value on ho@the su\$lier @ll \$erform @th traffic. Lo@ever this number can be cost2 for the carrier i6 the destination has a hi0h cost e.0. Cuba or) atellite 5hones#.

The 4 o+5 mar>et offers a @eb based \$latform named Chec>7 2Routes I1J, @hose 0oal is the automatic benchmar> o6 a 4 o+5 carrier destination. Lo@ever, it has a hi0h cost M\$3.month# and the results are not al@a2s 0ood. Chec>7 2Routes on2 anal2Ces the si0nalin0 o6 the call and does not ta>e into account the media audio \$ac>ets#, ori0inati0 a hi0h amount o6 false \$ositives since the audio is im\$ortant for the detection o6 ?alse Ans@er) u\$ervision an undesirable common 4 o+5 issue#1%.

)ince 4 o+5 carriers have a business d2namism in @hich time is im\$ortant for usin0 the volatile offers o6 the su\$lier, it is necessar2 to accelerate the dia0nosis \$rocess o6 \$ossible \$rofit o\$ortunities. This lies in the \$rom\$tness o6 the anal2sis derived from the testin0. =msiricall2 it has been sho@n that the suitability o6 a 4 o+5 carrier for traffic termination de\$ends on several time \$arameters related to the used \$rotocol and the resultin0 audio comin0 from the ans@er o6 the end user 18,3J. Therefore, the \$ro\$osed methodolo2 aims to e/ \$loit the information @hich lies @thin the 4 o+5 \$rotocols and \$ac>ets si0nalin0 and media#, so the 0rade o6 a \$articular 4 o+5 carrier destination can be determined @th little human intervention. It also has the 6nal 0oal o6 shortenin0 the time \$ent in the dia0nosis o6 ne@business o\$ortunities.

2. Related work

There has been a lot o6 @or> on ho@to measure Nualit2 o6)ervice No) # and Nualit2 o6 =/ \$erience No=# in 4 o+5 net@or>s. The 6rst as\$ect 6ocuses main2 on the measurement o6 net@or> \$arameters such as dela2, Gitter and \$ac>et loss, es\$ecial2 ins\$ired b2 the mechanisms used in conventional tele\$hone net@or>s 14*J, in @hich the \$erceived)eech Nualit2 is the most im\$ortant No) metric. n 14"J an interestin0 surve2 o6 the 4 o+5 technolo2 is \$resented. 7 easurin0 No= is more difficult because it de\$ends heavil2 on certain sub@ective as\$ects o6 difficult measurement, as indicated in I(!' (4J.

The +TU defines No= as: OA measure o) t*e o#erall acceptabilit o) an application or ser#ice, t*e percei#e\$ subjecti#el b en\$-userO Unli>e tele\$hone net@or>s, in net@or> 4 o+5 net@or> conditions can constant2 var2 in re0ard to @hat the \$erce\$tion in one moment ma2 be res\$ect to another. n I(!J a No= anal2sis is done in a \$eriod o6 *!" da2s, and it @as 6ound that in addition to the technical metrics dela2, Gitter#, as\$ects such as- device t2\$e, o\$eratin0 s2stem, user interaction time, ma2 affect the 7 easurement o6 No=.) \$eci6call2 in that stud2, it @as sho@n to tend to decrease si0htl2 @th time. A similar result is confirmed in I((J @here it is su00ested that the measurement can be carried out in' situ, instead o6 \$erformin0 it in controlled environments, due to the 0reat diversit2 and <uantit2 o6 6nal devices that can affect the measurement o6 No=. Additional2, there ma2 be even social as\$ects that affect such measurement, as indicated in I(4J. n this article @e develo\$ a non'intrusive al0orithm based on 7 achine Hearnin0 to \$erform the \$rediction o6 No= based on some mathematical models such as = '7 odel I4!J, 9 ?H 9 eber ?echner Ha@#14(J and 5=) N 5erce\$ual =valuation o6)eech Nualit2# 144J. The results @ere ver2 satisfactor2. n I(&J, a 5=) N modification is \$erformed usin0 the N5=) N ne@5erce\$ual =valuation o6)eech Nualit2# al0orithm to measure the im\$act o6 some metrics on the de0radation o6 4 o+5 net@or>s.

7 ore detailed studies on No= can be 6ound in I(1, (%J and I(3J, @here a tour is made o6 the main measurement techni<ues. n I(8J @e revie@the relationshi\$ o6 No= vs the \$rice \$aid b2 the user, and 6ocuses main2 on the content o6 the \$oint o6 vie@ o6 the \$rovider.

Research \$a\$ers li>e I*!" ,**J 6ocus their ob@ectives on the <ualit2 o6 service offered b2 4 o+5 com\$ared to that offered b2 5) TN. 9 or>s I*!" ,*(J use the information contained @thin the interconnection \$rotocols and aim to evaluate the \$erformance o6 the 4 o+5 net@or> but not a \$articular destination o6 a 4 o+5 carrier. Related to voice reco0nition and voice activit2 detection 4 AD#, @or>s li>e I*4,*&J com\$are several al0orithms used for 4 AD. The research I*&J includes 6or time domain the) hort' Time Avera0e 7 a0nitude ?unction A7 #,) hort' Time Avera0e Pero' Crossin0 Rate PCR#,) hort' Time Auto Correlation ?unction,) hort' Time Avera0e 7 a0nitude Difference ?unction A7 D?# and 6or fre<uenc2 domain ?ourier anal2sis. Results sho@ that each al0orithm has its o@n advanta0es and disadvantages. Nevertheless, the combination o6 them can hel\$ diminish their disadvantages I*&J. The research \$a\$er I("J uses su\$sort vector machines) 47 # as the soft'com\$utin0

technique along with robust features of audio signals in order to classify their frames as ACT= or +NACT=. In I*1J features based on energy and Pero Crossin Rate are used in order to classify audio frames, b2 means of rules, into one of the following three classes: voiced, Unvoiced or silence.

In this work is proposed a methodology for 4 o5 call classification which helps carriers grade the destinations of their subscribers. Some audio features used in voice recognition algorithms along with a 4 7 are implemented in order to discern between voiced and unvoiced audio signals.

3. Proposed approach

This work too into consideration the communication structure presented in [1,8,*], along with the methodologies proposed by [8,*] for voice quality in 4 o5 networks. Figure 1 shows a block diagram of the proposed methodology which adds the parameter =/traction and Analysis block to the approach of [8,*]. The approach is based on a database which stores the test numbers used for calling the destination, then a traffic generator originates the 4 o5 calls. e.g. asteris# which are sent to the destination and finally the grade is determined. These tasks will be further explained in the next subsections.

3.1. Database

In order to grade a 4 o5 carrier offer, it is necessary to call the particular destination using the data of the local carrier and emit an opinion according to the connectivity result. This is performed through various carriers and destinations, a database which contains an organized list of subscribers, destinations and test numbers is needed. This database contains a list of test numbers which need to be dialed in order to determine whether the particular carrier is suitable for handling the 4 o5 traffic, e.g., a subscriber John Doe offers Colombia 7 mobile T100 to the Local Carrier, a number of calls is then dialed to 866 " " " " " " " " numbers which are previously stored in the database.

3.2. Traffic Generator

An important part in the automation of call grading is the generation of traffic that will be sent to the subscriber of the local carrier. It becomes necessary the communication between a switch and the database described above so the calls can be routed accordingly. A switch performs call control. This is related to functions which process a phone call and offer characteristics of telephone ringing tone, busy tone, off hook or dial tone, caller ID, etc. A switch also coordinates the routing of signal in messages which are necessary between networks that wish to communicate.

As it is shown in Figure 1, the traffic generator sends calls to the local carrier, which are then routed to their corresponding subscribers by the data of the local carrier. There is no direct interconnection between the traffic generator and the subscribers. The switch used in this work is a Renband Netone.

3.3. Sniffer

This task belongs to the capture derived from the traffic generation and sharing of packets. Its goal is to store relevant

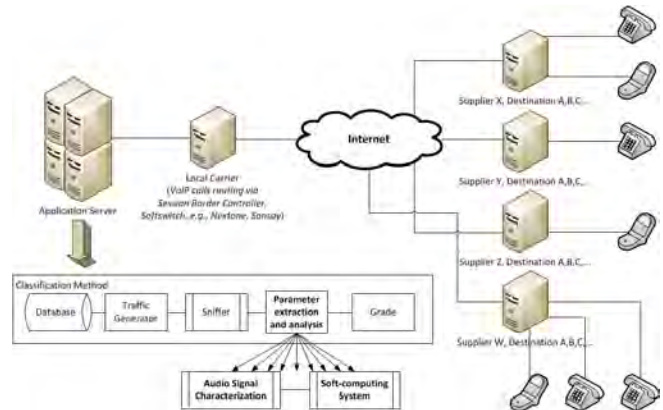


Figure 1. Communication diagram and proposed methodology.

Source: The authors.

information in order to grade call connectivity. Sniffers are used to capture network data without redirection or altering them. They can be found as software applications or hardware devices connected separately from a switch, although they can be part of it as well. The sniffer used for collecting data is Wireshark.

3.4. Parameter extraction and analysis

After the capture, it is necessary to extract and analyze some parameters which serve to grade the call connectivity. This task corresponds to the emulation of the reasoning made by the members of the technical support department of the local carrier network operations center, N, C#.

Based on the experience of 4 o5 carrier technicians, the grade of the destination of a carrier depends on several factors. A survey was performed in the company =stel Communications a 4 o5 carrier in order to determine which parameters are used to grade the call connectivity. Since the test results were stored in the e-mail account of the network operations center N, C#, each message had in its body the main parameters used for deciding whether the tests were successful or not. In 18 tests made by technicians, requested in the first days of March 2008, 5 selected =stel Communications used only 2 for educational purposes; the parameters used for grading the performance of the carrier regarding call connectivity are shown in Figure 2. These parameters are described below for the session initiation protocol (SIP).

- 5DD: Set dial delay. 5DD corresponds to the time difference between the +N4 +T= message sent by the client and the answer of the 200 OK session description sent by the server. It is also the time difference between the +N4 +T= message and an answer of the 200 OK or 404 which indicate an issue with the session establishment. It is usually given in seconds by most formats [8]. It is used to measure the time the server takes to respond to a request of a session establishment. As the 5DD becomes higher, the connection is said to have a poor performance [13,*].
- Ring Time: The ring time corresponds to the time difference between the 200 OK message received by the

client from the server and the message ! " " , U sent from the server to the client, letting this last >no@that the call @as accepted b2 the termination. This ! " " , U message is 6ollo@ed b2 an ac>no@ed0in0 message ACU# sent b2 the client to the server. Durin0 this time after the first *8T is sent#RT5 \$ac>ets are shared and an alert starts to be heard on the client side rin0 bac> tone or music tone# I8J. This \$arameter measure the time @hich the end user ta>es to ans@er the call. #t can indicate @hether there is an issue @ith the communication. ?or instance, i6 there are several calls sent to a\$articular destination @hose rin0 time is lon0 enou0h for different numbers, it @ill mean that the communication is not 0ood I3,*3J. 4 o+5 also can 0enerate a 6a>e rin0 bac> tone to the client @hich can lead to undesirable channel occu\$ation.

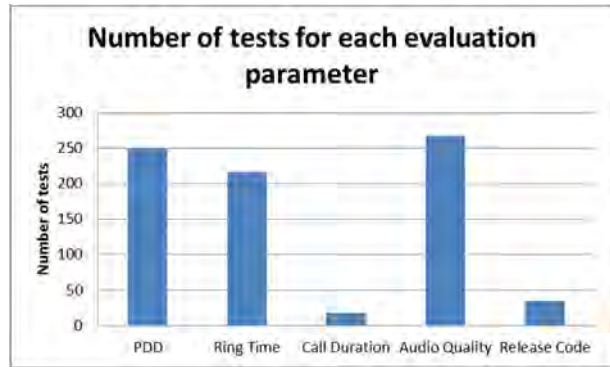
- **Call Duration-** This \$arameter is defined b2 the time difference bet@een the ACU message sent b2 the client, @hich 6ollo@as the ! " " , U message, and the QY= message sent b2 an2 o6 the \$eers lettin0 the other one >no@that the call has ended I8J. This \$arameter can \$oint out i6 there is a communication issue, e.0., @hen there are several calls sent to the same destination different numbers# and their duration is ver2 lo@ less than &or (seconds#.
- **Audio Nualit2-** This \$arameter belon0s to the human \$erce\$tion o6 the audio @hich comes as a result o6 call conversation. ?or the \$resented surve2 it @as considered onl2 @hen RT5 \$ac>ets @ere transmitted, i.e., @hen the call ran0, did not rin0, @ent to voicemail, did not \$resent noise, @as ans@ered b2 a \$erson, b2 an +4 R or @as bein0 billed.
- **Release Code-** This \$arameter is ta>en into consideration to discard si0nalin0 \$roblems in 4 o+5 calls. Accordin0 to I8J) +5 \$rotocol emits several messages to alert the client about the \$rocess o6 each call rin0in0, no channel available, on hold, bus2, etc.#

?i0. ! re\$resents a surve2 made at =stel Communications on @hich \$arameters are the most relevant for technicians \$eo\$le @ith e/ \$ertise in the area o6 4 o+5 call 0rade#, the \$arameters 5DD \$ost dial dela2#, Rin0 Time and Audio Nualit2, are the most relevant for them. Call Duration and Release Code @ere not that relevant but @ere also ta>en into consideration. #n order to 0rade Audio Nualit2, N, C members need to establish @hether the audio from the end user has voice or not.)ince soft' com\$utin0 can emulate the reasonin0 o6 a human, it is \$ossible to emulate the decision made b2 N, C members. ?irst a vector o6 features can be e/ tracted for the 4 o+5 calls. Then the2 can be classified b2 means o6 a \$attern reco0nition al0orithm. The latter is one o6 the several a\$ \$lications o6) u\$sort 4 ector 7 achines) 4 7 # I! " ! ! J.

The classes used to classif2 4 o+5 calls are sho@n in Table *.

3.5. Grade

)ubse<uent to \$arameter anal2sis, a 0rade for the destination o6 the carrier needs to be concluded. This is done b2 ta>in0 into consideration the classification o6 several calls sent to the 0ate@a2 o6 the su\$ \$lier, and



?i0ure! .) urve2 o6 =stel Communications.
) ource- The authors.

Table *.
, ut\$ut Classification Classes.

Class	Description
*	Call Re@ected
!	5ossible ?A)
(	Call Not Connected @ith Li0h RQT or Li0h 5DD
4	Call Not Connected @ith Ho@RQT and Ho@5DD
&	Call Connected @ith Li0h RQT or Li0h 5DD
1	Call Connected @ith Ho@RQT and Ho@5DD

) ource- The authors.

0ivin0 an o\$ \$inion related to the \$ertinence o6 the su\$ \$lier for traffic termination. There is not a \$recise number o6 calls that should be anal2ed. This is decided b2 the \$erson @ho \$erforms the tests. 9 hen the amount o6 destinations or su\$ \$liers that need to be tested is lo@, five or si/ calls are sent b2 technicians to the 0ate@a2 o6 the su\$ \$lier. Lo@ever, @hen the number is lar0e, 6e@er calls are sent in order to accelerate the testin0 \$rocess and emission o6 results. This can be misleadin0 since a lo@ amount o6 calls mi0ht not re\$resent the successful o\$eration or failure o6 the destinations o6 the su\$ \$liers. Also as stated before, for statistics, the more the test sam\$les, the more reliable the outcome.

. Results and e! aluation

The \$ro\$osed methodolo02 aims to com\$are it\$el6 @ith e/ \$ert >no@ed0e >no@ed0e ac<uired b2 technicians o6 4 o+5 carriers#. A total o6 ! %&' calls @ith their corres0ondin0 audio @hen \$ossible# @ere e/ tracted from Chec>7 2Routes \$latform. These calls @ere classified into each o6 the si/ classes o6 Table * b2 means o6 e/ \$ert >no@ed0e \$eo\$le @ith e/ \$ertise in the area o6 4 o+5 call 0rade#. ?irst, classes @hich did not involve audio @ere classified, based on time \$arameters Class *, Class (and Class 4#. Then, classes that involved audio Class !, Class 4 and Class &# @ere classified based on the anal2sis o6 the audio. Lere the e/ \$ert determined @hether the audio from the end user had voice or not. Thus, com\$arin0 the classification 0iven b2 the e/ \$ert @ith that 0iven b2 the Chec>7 2Routes, it @as \$ossible to determine that the accurac2 o6 Chec>7 2Routes on

identifying A) as 18V and the accuracy on determining calls recorded connected as %.

In order to emulate the human decision making for A) detection, audio features were analyzed. Derived from this task, some parameters that served as inputs to a soft' computing classifier were established. Then, cross validation was computed as a way to objectively conclude the accuracy of the proposed classifier. These tasks are described in the next subsections.

4.1. Audio analysis

405 carrier technicians are the ones who analyze the audio of the calls and determine whether it has voice or not. The standard low level features for audio analysis described in [14] can help to computationally solve this problem with little human intervention.

From the 18' total calls 418 have audio files. These are .wav files with 8 kHz sampling rate. They do not all have the same duration. In order to determine whether the audio file had voice or not, standard low level features were analyzed. Each file was segmented into 16ms audio frames stationary audio [14] and a 8V overlaid as used in [8]. Also low amplitude samples were replaced by zero since they seem to be related to background noise [11]. This was done by taking the mean of the average absolute amplitude of the first 16ms of each audio file, since in this time frame no voice should be present in a call there is a delay in starting the call conversation and greeting. This resulted in replacing by zero the amplitudes according to the equation $|s_n| < 0.0004$, where s_n is the original digital audio signal.

The main concern in this part of the research was to differentiate ring tones from voice. The variability of the standard low level features values resulted in being higher when voice was present in the audio file, since ring tones are sinusoids. Therefore, second order statistics of the features could help in order to differentiate voiced from unvoiced signals [11].

A 47 for pattern recognition was used for classification, based on the 18' samples and the second order statistics of the standard low level features. This 47 could also help to establish which parameters were the best suited for the classification task. Therefore, trial and error tests were implemented increasing the number of parameters until the highest possible accuracy was found. A computer running Hínu?edora 14 bits, Qee 7 iracle distribution with Intel Core i7 47 C5U W! ("RLC 4 cores and 1 RQ 6RA7 was used for simulation. The library H+Q 47 [11] was used along with 7 ATHAQ for carrying out the experiments.

The input parameters for the system after correlation coefficients analysis to discard any high linear dependence among parameters are listed below.

*. 5DD.

1. Ring Time.

(. Duration.

4.) standard deviation of the)hort' time Average = 02.

&) standard deviation of the)hort' time Pero Crossin0 Rate.

1.) standard deviation of the) Spectral Roll , 66

%) standard deviation of the)hort' time Average = 02 samples higher than zero.

8.) standard deviation of the)hort' time Pero Crossin0 Rate samples higher than zero.

3.) >eness of the)hort' time Average = 02 samples higher than zero.

*") >eness of the)hort' time Pero Crossin0 Rate samples higher than zero.

**.) >eness of the) Spectral Roll , 66 samples higher than zero.

*!) >eness of the) Spectral Centroid samples higher than zero.

*(.) standard deviation of the derivative of)hort' time Average = 02 samples higher than zero.

*4.) standard deviation of the derivative of)hort' time Pero Crossin0 Rate samples higher than zero.

*&) standard deviation of the derivative of) Spectral Roll , 66 samples higher than zero.

*1.) standard deviation of the) Spectral ?lu/.

4.2. Support vector machine

It is known that in order to use soft computing for classification, it is necessary to have similar amount of samples per class so the system can be trained well [18]. The amount of samples per each class are shown in Table 1. Prior to selecting 47 to perform the classification task, Artificial Neural Networks were considered. However, in order to avoid the risk of overtraining and time performance due to hidden layers and number of neurons [11], 47 were selected. A 47 was implemented to classify 405 calls, based on the classes shown in Table 1 with sixteen parameters as inputs.

The 47 as follows were validated using 10 fold Cross validation [18]. First, a single class as follows was validated for the classes presented in Table 1. Second, a two class as follows was validated that confronted Class 1 possible? A) # against Class & Call Connected with Lih 5DD or Lih RQT# and Class 1 possible? A) # against Class 1 Call Connected with Ho@5DD and Ho@RQT#. The radial basis function RQ?# kernel was used for the 47. This kernel has two parameters C, γ that are not known beforehand [13]. Therefore, a grid search was conducted in order to find the parameter values that outcome the best accuracy for the problem stated. Training sequences of C and γ is a practical method to identify good parameters for e/ample, $C = 10^{-8}, 10^{-4}, 10^{-2}, \dots, 10^2$ and $\gamma = 10^{-8}, 10^{-4}, 10^{-2}, \dots, 10^2$ [11].

Table 1. Amount of samples per Class

Class	Number of Samples
*	11
!	88
(	44
4	441
&	48
1	43*

Source- The authors.

4.1. *.) i/ Class a\$roach

A) 4 7 @as used for call classification o6 the si/ classes already \$resented in Table *. =ach call had *1 \$arameters. Those \$arameters @ere used for trainin0 and testin0 the) 4 7 . The) 4 7 out\$ut @as the class to @hich each in\$ut call belon0ed. ?rom the 0rid search the best cross validation overall accurac2 @as 3(.31V and the best C and 7 @ere ! *% and ! % res\$ectivel2.

The result o6 the *% fold Cross validation confusion matrix combinin0 the results o6 *% tests matrices is sho@n in ?i0. (. #t can be seen that for most classes the accurac2 @as higher than 3"V. Althou0h ?A) detection @as 8! %& tar0et class ! #, it increases the accurac2 o6 Chec> 2Routes 18V \$resented in section 4#. Also it increases the accurac2 for classes o6 calls that connected \$ro\$erl2. ?rom this result, it can be said that the) 4 7 is more trust@orth2 for the classification o6 \$ro\$erl2 connected calls. Lo@ever ?A) detection accurac2 is better com\$ared @ith Chec> 2Routes.

4.1.1. T@o class a\$roach

?or this a\$roach, the) 4 7 @as onl2 used for classification bet@een Class ! 5ossible ?A) # and Class & Call Connected @ith Li0h 5DD or Li0h RQT# and bet@een Class ! 5ossible ?A) # and Class 1 Call Connected @ith Ho@ 5DD and Ho@ RQT#. The decision for the im\$lementation o6 this a\$roach @as based on the fact that a similar amount o6 calls @as available for Class ! , Class & and Class 1. Therefore, i6 the classes & and 1 @ere combined to form one sin0le class, there @ould be a mismatch in the number o6 sam\$les since the ne@ class @ould have about t@o times the amount o6 sam\$les for 5ossible ?A) . The user can

establish a threshold for 5DD and Rin0 Qac> Tone values. =ach carrier can define @hat for them is a lo@ or hi0h 5DD and a lo@ or hi0h Rin0 Qac> Tone. ?or each call the same *1 \$arameters @ere considered. Those \$arameters @ere used for trainin0 and testin0 the) 4 7 . The) 4 7 out\$ut classified the calls in Class ! , Class & or Class 1 de\$endin0 on the user threshold.

T@o 0rid searches @ere \$erformed. The first one involved the) 4 7 for classification o6 Class ! and Class & . The values o6 C and 7 that 0ave the best overall *% fold Cross validation @ere ! % and ! % res\$ectivel2. The second 0rid search involved the) 4 7 for classification o6 Class ! and Class 1. The values o6 C and 7 that 0ave the best overall *% fold Cross validation @ere ! % and ! % res\$ectivel2. 5articularl2 for this case, the values o6 C and 7 for these t@o different) 4 7 s resulted to be the same.

The results o6 *% fold Cross validation are sho@n in ?i0. 4 and ?i0. & #t can be seen that ?A) detection for this a\$roach increased the one 0iven b2 the si/ class a\$roach. Also it can be seen that the differentiation bet@een Class ! ?i0. 4 Class *# and Class & ?i0. 4 Class ! # is more difficult to discern b2 the) 4 7 than the differentiation bet@een Class ! ?i0. & Class *# and Class 1 ?i0. & Class ! # 0iven that the accurac2 is better @hen classifi2in0 Class ! vs Class 1. This result ma2 be related to an inner relationshi\$ that 5DD, RQT or Duration o6 the calls ma2 have @ith ?A) , but it is not a\$\$arent.

% Discussion

Table (sho@as the accurac2 o6 the classifier com\$ared @ith Chec> 2Routes for each o6 the) 4 7 a\$roaches already described. 9 e can see that Chec> 2Routes classifies Classes (and 4 and Classes & and 1 as one.

Confusion Matrix of 10-fold Cross-validation

Output Class	1	2	3	4	5	6	
1	3620 13.2%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	0 0.0%	100% 0.0%
2	0 0.0%	4448 16.2%	0 0.0%	0 0.0%	362 1.3%	153 0.6%	89.9% 10.4%
3	0 0.0%	29 0.1%	4270 15.5%	0 0.0%	0 0.0%	0 0.0%	99.3% 0.7%
4	0 0.0%	0 0.0%	60 0.2%	4460 16.2%	0 0.0%	0 0.0%	98.7% 1.3%
5	0 0.0%	549 2.0%	0 0.0%	0 0.0%	4354 15.8%	98 0.4%	87.1% 12.9%
6	0 0.0%	354 1.3%	0 0.0%	0 0.0%	84 0.3%	4659 16.9%	91.4% 8.6%
	100% 0.0%	82.7% 17.3%	98.8% 1.4%	100% 0.0%	90.7% 9.3%	94.9% 5.1%	93.9% 6.1%
	1	2	3	4	5	6	

?i0ure (. *% fold Cross validation Confusion Matrix / .
) ource- The authors.

Confusion Matrix of 10-fold Cross-validation Class 2 vs Class 5

Output Class	1	2	
1	4582 45.0%	286 2.8%	84.1% 5.9%
2	798 7.8%	4514 44.3%	85.0% 15.0%
	15.2% 14.8%	94.0% 6.0%	89.4% 10.6%
	1	2	

?i0ure 4. *% fold Cross validation Confusion Matrix / Class ! vs Class &.
) ource- The authors.

Confusion Matrix of 10-fold Cross-validation Class 2 vs Class 6

Output Class	1	2	
	4958 48.2%	162 1.6%	96.8% 3.2%
	422 4.1%	4748 46.1%	91.8% 8.2%
	92.2% 7.8%	96.7% 3.3%	94.3% 5.7%
	1	2	Target Class

Figure 6. 10-fold Cross-validation Confusion Matrix Class 2 vs Class 6
Source: The authors.

Table 4.

Comparison of Accuracy of Check & Routes and Proposed Approach.

Class	Description	Check & Routes	Si (Class) &	*wo Class) &
*	Call Rejected	***V	***V	***V
!	Possible? A)	18V	81.9V	88.1V
(, 4	Call Not Connected	***V	33.4V	***V
& 1	Call Connected	96V	31.8V	3&4V

Source: The authors.

Therefore, in order to compare the accuracy of the proposed classifier, the combination of accuracies for classes (and 4 and classes & and 1 were compared. From the si/ class approach, it can be seen that the proposed 47 classifier is superior to that given by Check & Routes. For the t@ class approach, the overall accuracy of the classifier was compared by the combination of the correct classified calls for Class ! and the combination of the correct classified calls for Classes & and 1. It can be seen that the t@ class approach increases the overall accuracy of Check & Routes and the si/ class approach as well.

Call Rate using the proposed methodology also improves the efficiency of 40-5 call testing, in terms of time, by using computational technologies to bypass human analysis. In this way, calls are sent to the destination carrier, a human takes around 3 minutes to perform this task. However, when using a computational technology that can dial the calls simultaneously and analyze by itself the result of the calls, around 1 minute is sent. Table 4 summarizes this comparison. The parameter =/ traction value is the mean of the time sent and analyzed each one of the 1% total calls. The 47 analysis value was computed as the average time that an 47 takes to analyze each one of the 1% calls *1 parameters# times *. Finally, the call Rate was determined as the time 7 ATHAQ computes a certified

Table 4.

Time Sent Testing and Analysis calls#

Human	Check & Routes	Proposed	approach
		Call dialing and storing	~ 3 min
~ 3 min	~ 3 min	Parameter extraction	~ 1.14 s
		47 analysis	~ 1.14 s
		Rate	~ 1.14 s

Source: The authors.

mean. No such as in that the commercial department of the 40-5 carrier needs to test (destinations with the constraint of testing calls per destination, using the same math, a technician would need (minutes to test for the best scenario test numbers available, fast dialing, acute hearing, no pause between tests, etc. However, Check & Routes would take, for the same number of tests, at most four minutes such as in that it only sorts testing calls simultaneously. The proposed system would take at most five minutes. This result shows the gain in time when automating the testing.

Table 4 shows that the time sent by the proposed approach to provide a result is higher than the time sent by Check & Routes. However, despite that the proposed approach takes more time in providing a rate for the carrier, it is not considerable a few more seconds at most. Also the time that the system takes for analysis, can be reallocated compared to the time a technician would need to verify when Check & Routes gives a wrong analysis e.g. good classification for a destination that in reality presented ? A) #.

Conclusions and Future works

In this work a 47 which performed the processing of the parameters for call connectivity rate was implemented. This 47 also provided a better accuracy value for classification of unknown samples compared with common used methodologies previously described. This accuracy could be objectively determined by means of cross-validation.

The proposed methodology increases the accuracy for ? A) detection and for the connected calls detection compared to the automatic platform Check & Routes. The use of audio processing features along with a sort factor 7 achieves helped with this improvement. From si/ class classification, the proposed methodology gave an 81.9% of accuracy for for the ? A) detection. From t@ class classification the proposed classifier gave an 88.1V of accuracy for ? A). Check & Routes gave 18V of accuracy for this type of calls. On the other hand, the si/ class approach gave a 31.8V when classifying for the connected calls. T@ class approach gave 3&4V of accuracy for this case. Check & Routes gave a 96V for for the connected calls. It can be concluded also, that despite the proposed approach takes more time than Check & Routes to provide a result, the improvement in accuracy is worth the delay. Since Check & Routes is not so trustworthy with its results, technicians need to stay in order to have certainty that a particular destination has ? A) or is wrong. This

human involvement is hi0hl2 avoided @th the \$ro\$osed s2stem since its results are more reliable. As sho@n in Table 4, the im\$lementation o6 the \$ro\$osed s2stem reduces considerabl2 the time ta=en for testin0 com\$ared @th human testin0. This can become a lon0 term economic savin0s for the carrier since the human resources can reduce their @or>load for such a tiresome tas>.

?uture @or>s should focus on the im\$lementation o6 a different soft' com\$utin0 techni<ue such as decision trees or artificial neural net@or>s. Also, there ma2 be some other audio si0nal \$arameters that could hel\$ im\$rove the accurac2 o6 the current s2stem for ?A) detection. It is also recommendable to use more audio sam\$les that ma2 hel\$ the trainin0 o6 the soft' com\$utin0 classifier. This s2stem can also be im\$lemented as a soft@are \$latform and be tested @th real 4 o+5 traffic.

Acknowled+ements

9 e 0ratefull2 @ould li>e to than> the Universidad del Norte and the Colombian Rovernment's Departamento A\$ministrati#o \$e Ciencia, , ecnolog#a e Inno#aci#n C, HC#NC+A) #for their su\$sort on this \$ro@ect. This @or> has been su\$sorted b2 C, HC#NC+A) via the -!#enes In#estigati#ores e Inno#a\$ores. / 01 \$ro0ram.

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Maestría en Ingeniería - Ingeniería Eléctrica

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Design and optimization of a reverse electro dialysis stack for energy generation through salinity gradients

(area of research: Carlos Escobar; et al)

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Abstract:

A model for design of Reverse Electro dialysis stacks for energy generation is presented and solved. A new optimization function is proposed for $R>D$, which accounts for river water consume, net power density and thermodynamic efficiency of the process. The parameters of residence time and thickness of the compartments are successfully optimized using the new proposed function. Results suggest small residence time, compartments thickness, and transversal area and Q/A ratio for maximum energy generation.

Keywords: Reverse Electro dialysis; salinity gradient power; design; optimization.

Diseño y optimización de una celda de electrodiálisis inversa para generación de energía a partir de un gradiente salino

Resumen

Se presenta y resuelve un modelo para el diseño de celdas de electrodiálisis inversa. Se propone una nueva función de optimización para $R>D$, que tiene en cuenta el consumo de agua de río, la densidad de potencia neta y la eficiencia termodinámica del proceso. Los resultados sugieren que pequeños tiempos de residencia, espesores de los compartimientos de electrolitos, área transversal y relaciones Q/A de ancho del compartimiento para máxima generación de energía.

Palabras clave: electrodiálisis inversa; energía a partir de un gradiente salino; diseño; optimización.

1. Introduction

Salinity gradients are found in nature when rivers meet the sea. Artificially, they are found in desalination plants which have concentrated salt brines effluents that are usually discharged directly to the sea, and bring adverse impacts on vulnerable ecosystems like mangrove forests, salt marshes, coral reefs, or generally, low energy intertidal areas [1].

Estimations of practical global energy potential for salinity gradients between river and sea water, suggest that the world energy demand could be satisfied [2-4] for the Magdalena River in Colombia, taking into account its

environmental constraints, a technical potential for an installed capacity greater than 10,000 MW has been calculated [5], which makes it the sixth river with more extractable energy in the world [6].

Colombia is rich in both, river and sea water, and its oceanographic and climate conditions favor the harnessing of salinity gradient power (HSG) more than other tropical countries of marine energy [7]. This power could be a clean source of energy for Colombia, replacing coal plants, small diesel generators from rural and off-grid areas, and even used for cogeneration systems, mitigating environmental impacts in desalination plants [8].

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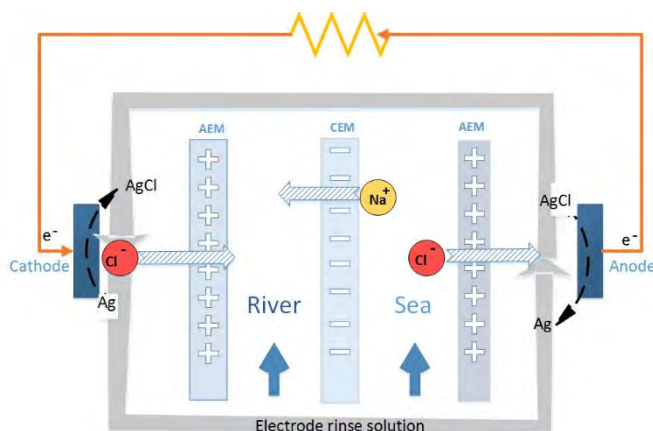
>lectrical \$o? er cannot be e0tracted under s\$ontaneous mi0in1 conditions, because the \$rocess is thermod3namicall3 irreversible E&F. The technologies for e0tractin1 (HI allo? to transform the diminution o5 Hibbs free ener13 available ? hen mi0in1 t? o solutions ? ith di\$fferent salt content, in electrical ener13, \$er\$ormin1 the mi0in1 under controlled conditions.

(everal technologies are bein1 develo\$ed for harnessin1 artificial or natural (HI E " % + E I ressure Retarded - smosis I R- #uses the- smotic \$ressure di\$fference? ith membranes selective for ? ater E 4, ' , E, Ca\$active = i0in1 uses the e0\$ansion and contraction e\$fect o5 the electrical double la3ers usin1 activated carbon ca\$acitors E ! E, and Reverse >lectrodial3sis R>D# uses the electrochemical \$otential di\$fference? ith ion selective membranes *>= # E 2E.

R>D is one o5 the most e0tensivel3 studied technolo13 in the recent 3ears, it has been demonstrated that it can be suitable for di\$fferent a\$\$lications li6e ? aste heat recover3 usin1 artificial solutions E) E, ? aste? ater treatment ? hen cou\$led ? ith biological \$rocesses E 8F and ener13 e0traction ? ith redo0 or ca\$active electrodes E + E. Due to its \$ossibilities and advantages, R>D is the focus o5 this ? or6.

Ji1. ' sho? s the s6etch o5 a R>D cell. * consists in a set o5 ion e0chan1e membranes, alternatin1 cation C>= #, and anion e0chan1e membranes A>= #, ? hich are char1ed ne1ativel3 and \$ositivel3 re\$ectivel3. Usin1 this membrane arrangement, river and sea ? ater \$o? bet? een membranes and in this ? a3 com\$artments are \$ormed. Due to the di\$fference in salt concentration bet? een the ? aters, there is an electrochemical \$otential di\$fference, ? hich is the motive force for ions to \$o? throu1h the membranes from the sea ? ater com\$artments, to the river ? ater com\$artments. This \$art o5 the s3stem is called ionic circuit, and it is in char1e o5 \$er\$ormin1 the mi0in1 \$rocess in a thermod3namicall3 reversible ? a3.

Usin1 this membrane circuit allo? s cations to move in one direction and anions to move in the o\$posite direction. As a result o5 the controlled ion movement, an electrical \$otential di\$fference arises in the membranes. The total volta1e obtained from the stack, is the sum o5 electrochemical \$otential o5 each o5 the membranes.



Ji1ure ' . (chematic vie? o5 a R>D cell.
(ource: The authors

*n order to convert the ionic \$u0 in the membrane circuit into electrical current, the 1enerated volta1e is used to \$er\$orm reversible reduction/o0idation reactions in the electrodes that allo? to trans\$ort electrons throu1h an e0ternal circuit, and thus \$o? er is \$roduced.

2. Theoretical model

2.1. Maximum obtainable energy

The theoretical available ener13 in mi0in1 m# a concentrated c# and a diluted d# solution, corres0nds to the Hibbs free ener13 o5 mi0in1 ΔG_m E 8F.

$$\Delta G_m = \sum_i G_{i,m} - (G_{i,c} + G_{i,d}) \quad ' \#$$

A here $G_{i,m}$, $G_{i,c}$ and $G_{i,d}$ are the Hibbs ener13 o5 the mi0, concentrated and diluted solution re\$ectivel3. A\$ter re\$lacin1 the definition o5 Hibbs free ener13 o5 each o5 the initial and \$inal states o5 the \$rocess ΔG_m becomes.

$$\Delta G_m = 2RT \left[F_c C_c \ln \frac{C_c}{C_m} + F_d C_d \ln \frac{C_d}{C_m} \right] \quad ! \#$$

A here R is the universal 1as constant 8. + ' 4 < /mol K#, T is absolute tem\$erature K#, F_c and F_d are volumetric \$o? o5 concentrated and diluted solution, and C_c , C_d , and C_m are the salt concentration o5 concentrated, diluted and mi0 solutions re\$ectivel3. J actor ! corres0nds to dissociation o5 NaCl. C_m , it is calculated as

$$C_m = \frac{V_c C_c + V_d C_d}{V_c + V_d} \quad + \#$$

2.2. Mass balance

Ji1. ! sho? s a mass balance scheme for concentrated and diluted com\$artments ? ith len1th L, ? ith b and thic6ness δ . A ater \$o? sin the 0 direction. Trans\$ort o5 ions throu1h the membranes occurs from the concentrated to the diluted com\$artments, ? hile ? ater \$asses in the reverse direction due to an osmotic e\$fect and the non%ideal behavior o5 membranes. The mass balance leads to the di\$fferential e0uations that describe the chan1e in salt concentration ? ithin the com\$artments in stationar3 state E " E.

$$\frac{dC_c}{dx} = \frac{b}{F_c} T_{NaCl}(x) - \frac{b}{F_c} C_c(x) T'_{water}(x) \quad 4 \#$$

$$\frac{dC_d}{dx} = -\frac{b}{F_d} T_{NaCl}(x) + \frac{b}{F_d} C_d(x) T'_{water}(x) \quad , \#$$

A here T_{NaCl} is salt \$u0 across the membranes mol /m' # and T'_{water} is volumetric ? ater \$u0 across the membranes m' /#. A ater trans\$ort is 1iven b3

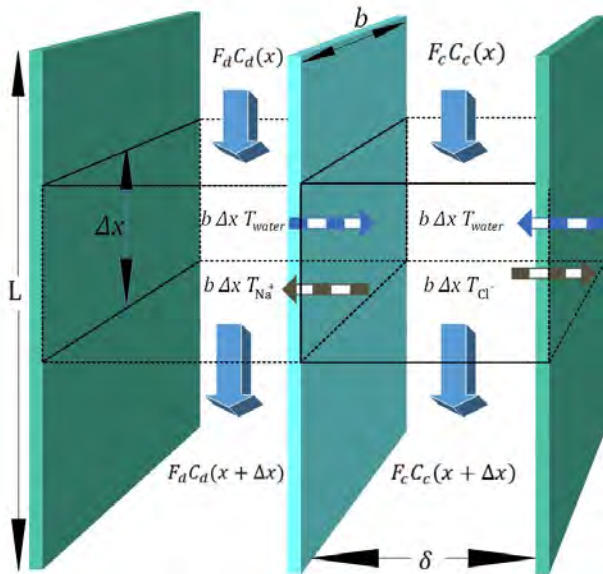


Figure 1. Mass balance for concentrated and diluted compartments. (source: The authors)

$$T'_{water} = \frac{2D_{water}}{\delta_m} (C_c(x) - C_d(x)) \frac{M_{water}}{\rho_{water}} \quad 2\#$$

Here D_{water} is the water diffusion coefficient m^2/s , δ_m is the membrane thickness m , M_{water} is water molar mass and ρ_{water} is water density. The factor of molar mass over molar density is added for making T'_{water} a volumetric flow.

Transport of NaCl through the membranes is driven by two major effects: migration of counterions due to electrochemical potential difference, and diffusion of coions due to nonidealities in membrane selectivity.

$$T_{NaCl}(x) = J_{ai}(x) + J_{mi}(x) \quad)\#$$

Diffusion transport is described by Fick's model.

$$J_{ai} = \frac{2D_{NaCl}}{\delta_m} (C_c(x) - C_d(x)) \quad 8\#$$

Here D_{NaCl} is the diffusion constant of salt through membranes. For describing migration, the following principle is used.

$$J_{mi} = \frac{1}{F} \frac{\Delta\varphi}{R_{cell}} \quad 8\#$$

Here $\Delta\varphi$ is the electrical potential, R_{cell} is the cell resistance and F is the Faraday constant, which is needed to convert coulombic flow into mol flow. $\Delta\varphi$ can be calculated with Nernst equation.

$$\Delta\varphi = \alpha_{CEM} \frac{RT}{F} \ln \left(\frac{\gamma_c^{Na^+}(x) C_c^{Na^+}(x)}{\gamma_d^{Na^+}(x) C_d^{Na^+}(x)} \right) + \alpha_{AEM} \frac{RT}{F} \ln \left(\frac{\gamma_c^{Cl^-}(x) C_c^{Cl^-}(x)}{\gamma_d^{Cl^-}(x) C_d^{Cl^-}(x)} \right) \quad ' '\#$$

Here α is the permselectivity of the membranes and γ is the activity coefficient of each of the ions in the different solutions. For diluted and concentrated solutions, activity coefficients may be estimated from the Pitzer model [14], which can be simplified for symmetric electrolytes to eq. (14).

$$\ln \gamma = |z_M z_X| f^\gamma + m B_{MX}^\gamma + m^2 C_{MX}^\gamma \quad ' '\#$$

$$f^\gamma = -A_\phi \left[\frac{\mu^{1/2}}{1 + b\mu^{1/2}} + \frac{2}{b} \ln(1 + b\mu^{1/2}) \right] \quad ' !\#$$

$$B_{MX}^\gamma = 2\rho_{MX}^{(0)} + \frac{2\beta_{MX}^{(1)}}{\alpha^2 \mu} \left[1 - e^{-\alpha \mu^{1/2}} \left(1 + \alpha \mu^{1/2} - \frac{1}{2} \alpha^2 \mu \right) \right] \quad ' +\#$$

$$C_{MX}^\gamma = \frac{3}{2} C_{MX}^\phi \quad ' 4\#$$

Here μ is the ionic strength of the solution, A_ϕ is the Debye-Hückel coefficient for osmotic function [14] for water at 25 °C, values of α and β are respectively 3 and values of $\beta_{MX}^{(0)}$, $\beta_{MX}^{(1)}$ and C_{MX}^ϕ vary depending on the electrolyte used [14].

On the other hand, the resistance of the cell is the sum of resistances of anion and cation exchange membranes R_{CEM} and R_{AEM} , the river water compartment R_d and the sea water compartment R_c .

$$R_{cell} = R_{CEM} + R_{AEM} + R_c + R_d \quad ', \#$$

The resistivity of the membranes is a property given by the membrane manufacturer. The resistance of the compartments ed (15) depend on the thickness of the compartments δ m , the molar conductivity Λ_m (m^2/mol) and on the solution concentration mol/m^3 . Λ_m 's dependent on concentration, but if a suitable value is used for low concentration compartment, calculated resistance of the river compartment is reliable [14]. As the sea water compartment resistance is much lower, its value has low influence on the total stack resistance. A correction factor is introduced for the volume occupied by the spacer material f_v , which is a measure of the increase in electrical resistance due to relative effect of spacers, such as tortuosity in the ion flow trajectory and decrease in available volume for solution to flow.

$$R_d = f_v \frac{\delta_{rio}}{\Lambda_m \cdot C_d} \quad ' 2\#$$

$$R_c = f_v \frac{\delta_c}{\Lambda_m \cdot C_c} \quad ')\#$$

2.3. Net power produced

Once the system of equations is solved through the flow factor (γ), local flow or density P_d delivered to an external circuit can be found. In the particular case of maximum flow or, external resistance R_u should be equal to the internal resistance R_i .

$$P_d(x) = \frac{1}{2N} J^2(x) \quad (8)$$

Here N is the number of cells, and J is the migration current multiplied by the Faraday constant A/m^2 . The factor 0 is due to the fact that area is duplicated because of the use of two membranes $C \geq 3 A \geq \#$. Total flow or density produced is obtained with the integration of P_d over the length of the compartment in the direction, divided by the total membrane area.

$$P_{d-total} = \frac{2Nb \int_0^L P_d(x) dx}{2NLb} \quad (8)$$

Net flow or density produced is calculated as the difference between total flow or density produced and hydrodynamic losses of the stack corrected for total membrane area.

$$P_{d-net} = P_{d-total} - P_{d-hydr} \quad (9)$$

Here hydrodynamic losses P_{d-hydr} are calculated as the pressure drop over the stack, times the volumetric flow of each stream, divided by total membrane area.

$$P_{d-hydr} = \frac{\Delta P_c F_c + \Delta P_d F_d}{2NLb} \quad (9)$$

For calculation of the pressure drop over the stack, Reynolds number is used to know flow regime of streams inside the compartments

$$Re = \frac{vD\rho}{\mu} \quad (10)$$

In this case v represents mean velocity, D is the hydraulic diameter, ρ is liquid density and μ is the dynamic viscosity. For parallel plates, hydraulic diameter is equal to 4 times the distance between them. Applying this equation to small cells (0.01 m) and a thickness compartment of 0.001 m, for low residence times, a Reynolds number of the order of 0.1 is obtained, which can be interpreted as laminar flow over the compartments. If the flow is laminar, pressure drop over the compartments is defined as:

$$\Delta P_c = \frac{2\mu L F_c}{b \delta_c^3} \quad (11)$$

$$\Delta P_d = \frac{2\mu L F_d}{b \delta_d^3} \quad (12)$$

Flow rate is calculated as the dimensions of the compartments over the residence time of the solutions.

$$F = \frac{Lb\delta}{t} \quad (13)$$

Figure 1 shows the behavior of total flow and hydrodynamic losses with residence time. From the figure it can be seen that very low values of residence times lead to very high pressure drops, which results in unrealistic values of net flow or J_{1+u} .

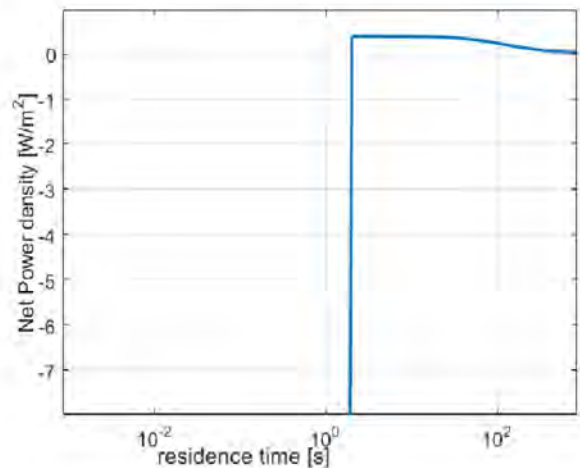
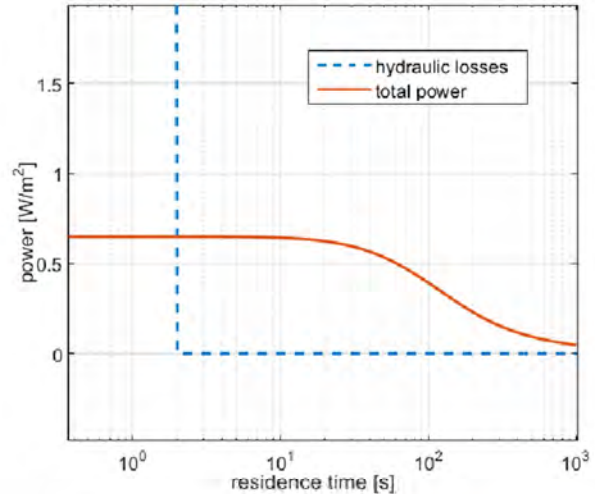


Figure 1. US# Total flow or density and hydrodynamic losses behavior with residence time. Do# n# Net flow or density 7 s residence time. (source: The authors).

From Figure 2, it can be seen that net flow is a parameter suitable for optimization because the function presents a maximum value. Nonetheless, it is important to notice that it does not account for thermodynamic efficiency of the process.

2.4. Lost work

For optimization is performed using only the net flow or density parameter, low values of thermodynamic efficiency

are achieved, due to the fact that favoring the flow rate density, leads to higher velocity of the processes and thus, more thermodynamically irreversible losses. Thus it is important to optimize taking into account thermodynamic efficiency of the process.

Cost of W_{lost} is defined as the difference between maximum energy theoretically obtainable and real energy obtained by the R>D stack, divided by total membrane area.

$$W_{lost} = \frac{\Delta G_m(C_{m, total}) - \Delta G_m(C_{m, out})}{2NLb} \quad (2)$$

$\Delta G_m(C_{m, total})$ corresponds to the available energy when the entire process is complete, as defined in eq. (1). $\Delta G_m(C_{m, out})$ is the actual extracted energy from the R>D stack.

$$\Delta G_{mz}(C_{mz, out}) = 2RT \left[F_c C_c \ln\left(\frac{C_c}{C_{c, out}}\right) + F_d C_d \ln\left(\frac{C_d}{C_{d, out}}\right) \right] \quad (3)$$

Here $C_{c, out}$ and $C_{d, out}$ are the outlet salt concentrations in the concentrated and diluted streams respectively.

Figure 4 shows the behavior of net energy density and lost energy with residence time. From Figure 4 it can be seen that W_{lost} further refines the optimization of net energy output, taking into account the lost energy when concentrations are not in equilibrium at the R>D stack outlet.

2.5. Optimization objective function

Using the parameters described in the previous section, a new optimization function is proposed. It includes all the response parameters relevant for optimization of R>D stacks mentioned in literature [17], and it combines them in one optimization function that has a mathematical minimum. This function allows to minimize lost energy and maximize net energy output, using energy density as the common unit to make calculations. Net energy is relative because optimization looks for minimization of objective function.

$$objective\ function = f_c * (W_{lost} - P_{d-net}) \quad (8)$$

Taking into account that fresh water is the limiting factor for energy generation through salinity gradients, and in order to minimize the use of this valuable resource, sea water fraction f_c is used in the optimization function to maximize sea water consume.

$$f_c = \frac{F_c}{F_c + F_d} \quad (8)$$

(Several individual parameters have been introduced in literature that account for energy efficiency or energy density to optimize energy output in R>D. Nonetheless an optimization function with a theoretical minimum that accounts for all of these parameters together had not been proposed until now. Figure 4 shows the behavior of the objective function with residence time. It can be observed

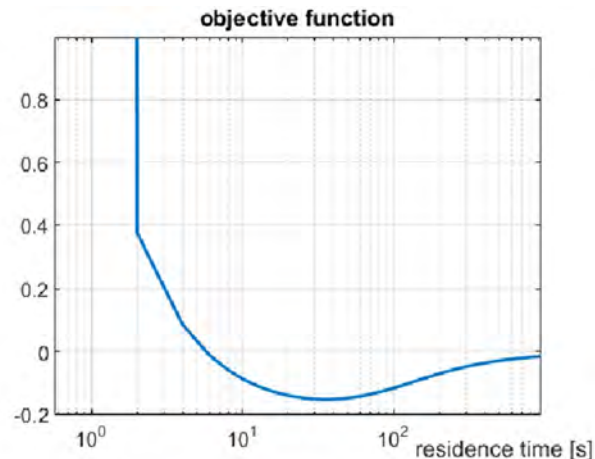
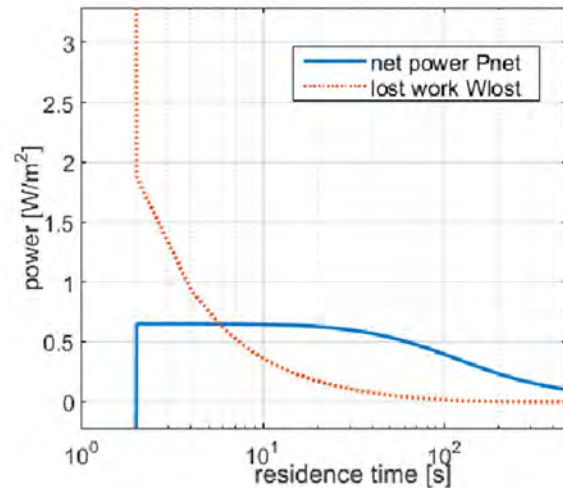


Figure 4. Comparison between lost energy and net energy with residence time. Does the behavior of defined objective function $(W_{lost} - P_{d-net})$ with residence time.
(Source: The authors).

that there is a minimum in the objective function, which lives at the same time maximization of net energy and minimization of lost energy and river water use.

3. Results and discussion

In order to validate the model with previous results reported in literature, parameters used for evaluation of the model are the same used by Terman et al. for a 10 cm cell [2]. Residence time for river and sea water as 2 s, obstruction factor as 1, $R_{CEM} = 5.9 \times 10^{-4} \Omega m^2$, $R_{AEM} = 1.63 \times 10^{-4} \Omega m^2$, membranes selectivity of 0.88, thickness of the compartments of 1 mm. Q_m , NaCl diffusion coefficient of $0.13 \times 10^{-10} m^2/s$ and inlet salt concentrations are 1.8 mol/m³ for concentrated stream and 0.1 mol/m³ for the diluted stream. The model was solved with MATLAB R software.

Figure 5 shows model results for current mode [3] and

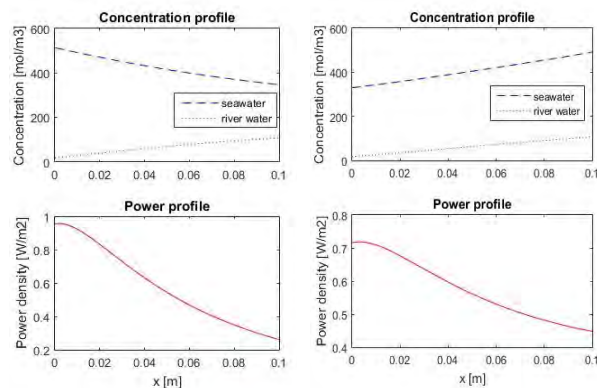


Figure 1. Model results for co-current operation. Left and counter-current operation. Right. Local concentration inside the compartments and local net $\dot{Q}$ or $\dot{Q}_{net}$ do not are shown. (Source: The authors).

counter-current mode. Right, which are in agreement with model and experimental results presented by Zerman et al. [2]. Counter current mode presents better ionic current distribution than co-current as may be seen from $\dot{Q}$ or $\dot{Q}_{net}$ profiles in Fig. 1. This may seem as an operational advantage, nonetheless, counter current operation introduces high local pressure differences between the compartments, which increases chances of possible leaks [1, 11].

Due to the fact that counter current operation presents more technical issues than co-current, and net $\dot{Q}$ or $\dot{Q}_{net}$ is very similar for both modes of operation, optimization is performed only for co-current mode.

After validation of the model is done with previous literature, optimization is performed for a stack with 10 cells, membranes and no spacers. Table 1 shows the effect of the length of the stack. $\dot{Q}$ is evaluated for a width of the compartment of 0.01 m. Optimized parameters are residence times of sea and river water, and thickness of the compartments.

Results of optimizations show that residence time of river water is higher than sea water, suggesting less river water consume for energy generation. This proves that optimization function, satisfactorily fulfills the requirement to reduce river water consume. For the optimization of the compartments thickness, results in Table 1 suggest that sea water compartments could be up to ten times the thickness of the river water compartment. This result is due to the fact that river water has more electrical resistance than sea water because of its low salt content.

Nonetheless, this last result may not be very practical in real conditions, because having a 10 micrometer thickness compartments for river water, could cause frequent clogging of the stack. Besides, it has been proven that a good anti-fouling strategy is to exchange the streams in the compartments every now and then, but in order to achieve it, it is necessary that the compartments are symmetrical [11]. Moreover, other energy generation methods have been proposed like using electric double layer capacitors instead of electrodes, but this method requires to exchange the water between compartments regularly [11]. Moreover, the advantage of the model is the possibility to choose the parameters to optimize. Thus, it could be interesting to optimize for symmetrical compartments.

Table 1.

Optimized parameters and net $\dot{Q}$ or $\dot{Q}_{net}$ obtained for different length of the compartments.

L [m]	t_d [s]	t_c [s]	δ_c [mm]	δ_d [mm]	P_{d-net} [W/m²]
0.01	8.8	1.4	1.8	1.1	1.42
0.02	8.2	1.4	1.8	1.1	1.42
0.04	8.2	1.4	1.8	1.1	1.42
0.06	8.2	1.4	1.8	1.1	1.42
0.08	8.2	1.4	1.8	1.1	1.42
0.1	8.2	1.4	1.8	1.1	1.42

(Source: The authors).

On the other hand, results for residence times for river and sea water after a series of other results obtained in literature [11]. Near velocities between 1 and 4 cm/s are recommended for river water, while higher velocities between 4 and 14 cm/s are recommended for sea water, depending on the compartment length and membrane area.

From Table 1 it can also be noticed that net $\dot{Q}$ or $\dot{Q}_{net}$ decreases when increasing cell length. As $\dot{Q}$ or $\dot{Q}_{net}$ is directly related to the cost of a R>D stack, increasing cell length will only increase cost, while decreasing economic efficiency or viability of the process.

Table 1 presents a comparison between P_{net} , P_{d-net} and thermodynamic efficiency η_T for the same values presented in Table 1, in terms of area. It is important to notice that, although smaller areas present in general higher total $\dot{Q}$ or $\dot{Q}_{net}$ generation and better thermodynamic efficiencies, it has a decreasing effect on net $\dot{Q}$ or $\dot{Q}_{net}$.

Natural processes follow the maximum entropy principle, sacrificing efficiency in order to let more $\dot{Q}$ or $\dot{Q}_{net}$. Thus it is reasonable to design R>D stacks with smaller areas because they favor net $\dot{Q}$ or $\dot{Q}_{net}$ per square meter membrane over thermodynamic efficiency, decreasing the cost of investment of the plant up to 20% according to the results in Table 1.

An optimization was performed in order to study the effect of the width of the compartment on net $\dot{Q}$ or $\dot{Q}_{net}$, and thermodynamic efficiency. Table 2 shows clearly how increasing cell length, increases thermodynamic efficiency of the process, due to the fact that longer stacks allow more ion exchange through the membranes, but they also increase hydrodynamic losses. (smaller width ratios achieve a higher net $\dot{Q}$ or $\dot{Q}_{net}$, and thus higher widths than lengths are recommended for stack design).

Table 2.

Comparison between net $\dot{Q}$ or $\dot{Q}_{net}$ and thermodynamic efficiency of the process with transversal area of the stack.

Area (m²)	P_{net} (W)	P_{d-net} (W/m²)	η_T
1	1.8	1.1	1.42
2	1.42	1.42	1.42
4	1.42	1.42	1.42
8	1.42	1.42	1.42
16	1.42	1.42	1.42
32	1.42	1.42	1.42
64	1.42	1.42	1.42
128	1.42	1.42	1.42
256	1.42	1.42	1.42

(Source: The authors).

Table 3.

Analysis of net power density and thermodynamic efficiency with area ratio for a constant area of 5 m².

b	b	δ	P_{d-net} (W/m ²)	η_T
1	"	"	"	"
1	"	"	"	"
2	"	"	"	"
1	"	"	"	"
1	"	"	"	"
1	"	"	"	"
1	"	"	"	"
1	"	"	"	"
1	"	"	"	"
1	"	"	"	"
1	"	"	"	"

(source: The authors).

Table 4.

Optimized parameters for the proposed cell design.

t_d s	t_c s	δ_c mm	δ_d mm	P_{d-net} A/m ²
0.005	0.005	0.005	0.005	0.005

(source: The authors).

Taking into account all the previous considerations, as well as technical and practical construction issues, a cell with dimensions 0.005 m and 0.005 m is proposed. For these dimensions, optimized parameters are shown in Table 4.

Concentration and power profiles within the compartments for the optimized design are shown in Figure 2. From the figure it is possible to notice that river water compartment develops a concentration profile, while seawater compartment does not. This happens due to the fact that smaller residence leads to higher volumetric flow for seawater, which causes that the channel in concentration of seawater inside the compartment is very small compared to the channel in concentration of the river water compartment.

It is also possible to notice that local power is higher at the fluid entrance, this is caused because there is higher concentration difference at the beginning, which is translated in more electromotive force, and thus more power.

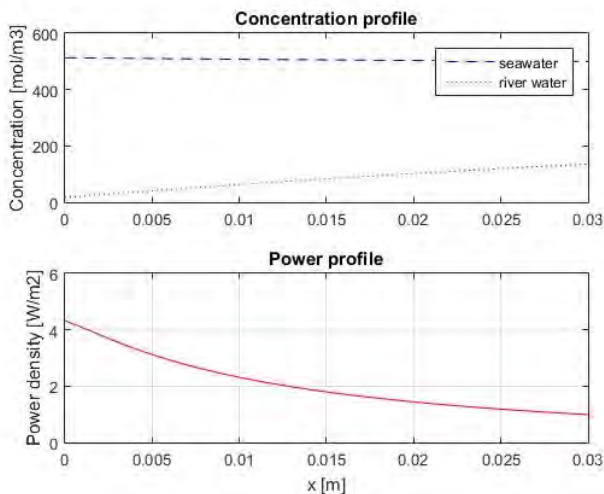


Figure 2. Concentration and power profiles for the optimized cell design.

(source: The authors).

Conclusions

A new proposed objective function was used for optimization of R/D stacks to achieve higher net power density after use, maximizes net power output, and introduces the concept of lost power as a factor in thermodynamic efficiency into account in the same units as net power density. This allows to calculate and find a theoretical minimum value of the difference between lost power and net power density. It was proven that the function has a mathematical minimum of 0.005, therefore accounting for all the parameters proposed in literature together in one function.

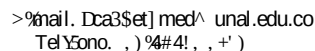
In comparison with other optimizations done in the past, the new optimization function will allow a straightforward and optimization of R/D stacks for different operation parameters. Results agree with optimizations performed in literature, and with linear velocities studied in different R/D studies. The optimization studied small areas and area ratios for obtaining better net power densities.

Acknowledgments

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- RC*D, """"%"""!%&+&2%2)!!.

Condensation and partial pressure change as a major cause of air flow. 70 Experimental evidence

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Abstract

The dominant model of atmospheric circulation is based on the notion that hot air rises, creating horizontal winds. A second major driver has been the biotic sum of the 98T# b3 6 high intense condensation is the prime cause of surface winds from ocean to land. Critics of the 98T argue that air movement resulting from condensation is isotropic. This paper shows the h3sics of 6 after condensation under mild atmospheric conditions, within a 4.8m tall closed system structure. The data show a significant correlation $r^2 = 0.456$, $p = 0.00044$ between observed air flow and partial pressure changes from condensation. The assumption that condensation of water vapour is always isotropic is therefore incorrect.

Keywords: Air flow; condensation; convection; anisotropic.

Condensation and the change in the partial pressure as a cause of air flow. 70 Experimental evidence

Resumen

El modelo dominante de la circulación atmosférica resume que el aire más caliente sube, generando así los vientos horizontales. La teoría de la bomba biótica 98T# propone un segundo mecanismo, en la cual la condensación intensa sea la causa primaria de los vientos superficiales. Los críticos de la 98T discuten que cualquier movimiento del aire resultante de la condensación sea isotrópico. Este artículo muestra la física de la condensación de vapor de agua bajo condiciones atmosféricas livianas, utilizando una estructura experimental diseñada para tal fin. Los datos demuestran una correlación altamente significativa $r^2 = 0.456$, $p = 0.00044$ entre los flujos de aire observados y los cambios en la presión parcial resultante de la condensación.

Palabras clave: Flujo de aire; condensación; convección; anisotrópico.

1. Introduction

Atmospheric convection, which leads to air mass circulation, is generally considered to result from the local atmospheric action as a heat engine, with the kinetic energy for convection deriving from differences in temperature, according to the general principle that hot air rises and cold air sinks: alarieva et al. (2004) in the biotic sum of Theor3

98T#, have argued that cloud formation and the resulting condensation, fuelled by evapotranspiration from closed-canopy rainforest, removes water vapour molecules from the atmosphere. That removal disturbs hydrostatic equilibrium and makes air circulate under the action of the evaporation/condensation force.

7vidence that surface air flow from the ocean to land is drawn in as a consequence of cloud condensation has come

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From a number of different sources. Roveda et al. [2] suggest that at 4 J N over Colombia the high rate of evapotranspiration from the dense rainforest and the consequent cloud formation draws in humid surface winds from the Pacific Ocean.

Critics of the 98 T argue that the movement of air which takes place during the condensation of water vapour is invariably an isotropic process, with the air moving from all directions simultaneously, thereby preventing a net, uni-directional flow. At the physical experiments, as undertaken and presented here, indicate instead that condensation can be anisotropic, thereby resulting in a net, uni-directional flow.

2. Methodology

To test the underlying physics of the impact of condensation upon airflow, a dedicated structure forming a square donut has been constructed. The experimental structure, Fig. 1, consists of 16 hollow columns, made of insulated 8NC, 4.1 m high internal, with an internal cross-sectional area of 0.8 m², connected at the top and bottom by tunnels 1.1 m long.

Access to each column is by means of an insulated 8NC door, 61th double glazed, to allow a view inside. To allow access of cooling refrigeration coils are located near the top of the right-hand column, around the four walls, connected to a 1/2 HP industrial refrigerator located some 4 m away on the floor of the laboratory. The cooling coils have a total surface area of 0.24 m² and take up one third of the cross-sectional area.

Calibrated sensors, including Class 1 thermocouples T₁, Rotronic accuracy 0.18R #h31rometers which also measure temperature R; ST₁, and barometric pressure 1aules 8*24!8 accuracy 0.2! R # 9 AR # provide measurements of changing conditions within the columns and tunnels every 5 seconds. A Novus 1011er transmits data from the four thermocouples and pressure 1aules to the computer. The T₁ 10 ultrasonic P indsonic accuracy 0.1R # anemometer UA₁, measuring every second, is sited in various locations in the upper tunnel during the course of distinct experiments. - ne location for the anemometer is "1" m from the floor of the upper tunnel and some "1" m from the junction between the tunnel and the right-hand column; another location is "1" m from the upper tunnel floor and close to the junction of the tunnel with the left-hand column, therefore 0.1 m away from the cooling elements.

C11ht6 ei1ht 1aue 6 ind\$as\$ are located at the left end of the top tunnel and at each of the bottom tunnels. These \$as\$ provide a visual indication of airflow direction when this is too slow to be recorded by the anemometer.

The directionality of an airflow is either clockwise or counter-clockwise using the right-hand column from the heating mat, past the cooling coils, and down the left-hand column. The T₁ anemometer does not record directionality when airflow falls below 0.1 m/s, and does not record air speed below 0.1 m/s. Because of the lack of the anemometer is mounted, a right-hand or clockwise airflow is recorded as 13in1 between "1" J and "1" %J, and a left-hand or counter-clockwise flow as 13in1 between "1" J & "1" J and +, "1" J & "1" J.

At the end of each experimental run, the flow is

condensate on the cooling coils melts and the rain is collected in a 1 liter bucket at its left end.

3. Equations

(standard physics) are applied throughout to interpret the experimental results. The three variables of temperature, barometric pressure and relative humidity are used to calculate the partial pressure of water vapour using the exponential equation of Clausius-Clapeyron, [2], $p_2 = p_1 \exp\left(\frac{h_{fg}}{R(T_2 - T_1)}\right)$, where p_2 is the partial pressure of water at T_2 , p_1 is the partial pressure of water at T_1 , h_{fg} is the latent heat of vaporization, and R is the gas constant. The saturated partial pressure of water, p_{sat} , at each temperature, T_1 , can be determined as follows:

$$\ln \frac{p_2}{p_1} = \frac{Q(T_2 - T_1)}{R T_2 T_1} \quad (1)$$

Eq. (1) can be rewritten as:

$$\log p_2 - \frac{Q(T_2 - T_1)}{R T_2 T_1 2.303} = \log p_1 \quad (2)$$

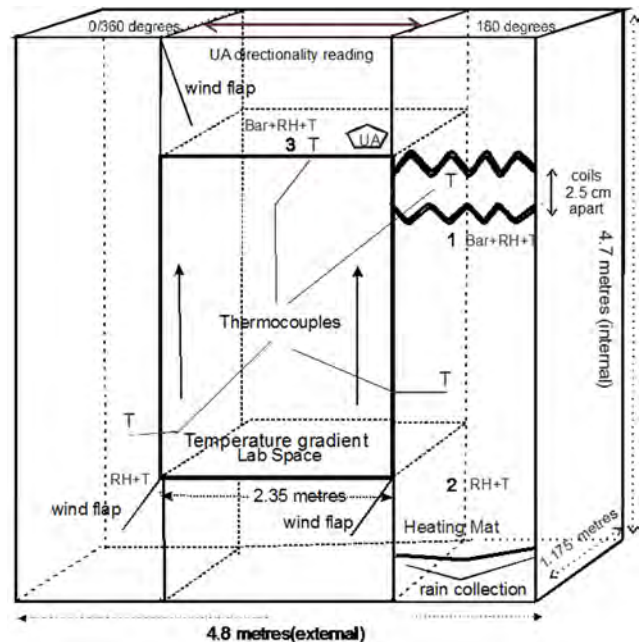


Figure 1. This diagram shows the position of the sensors: 9 AR # 10 Ultrasonic Anemometer UA₁, Thermocouple T₁, and Relative Humidity; 31rometer, which also measures temperature R; ST₁. The refrigeration coils, heating mat and rain collector are also shown. It illustrates the setup when the air circulation is clockwise, 1aue \$as\$ (ensors for R; ST have been placed at each of the three numbers at locations "1" # = +, and 9 AR at locations "1" # = +. Cocation "1" is "1" m below the junction of the upper tunnel with the right-hand column. Cocation "1" is "1" m above the floor of the right-hand column and location "1" is "1" m above the floor of the top tunnel. The top right T₁ is "1" m from the upper cooling coil. The left T₁ in the right-hand column is "1" m from the floor and the T₁ in the left-hand column is "1" m from the floor. The T₁ in the upper tunnel is "1" m from the junction with the right-hand column.

(source: 9 un3ard)

*n 7B. ' # = ! #, 9, latent heat o\$eva\$orisation is 4" .2, I > mol[&], 1, the ideal 1as constant, is 8.+ ' > V[&] mol[&]. The actual \$artial \$ressure o\$ 6 ater va\$our, p_1 , in the three numbered locations in H1. ' , is 1iven b3 multi\$13in1 the result b3 the relative humidit3, 1 %, as measured b3 the h31rometers.

The air densit3 is obtained throu1h the use o\$the eBuation o\$state for ideal 1ases, @ \$.82A

$$p = \rho R T \quad \text{+ \#}$$

P here p is the barometric \$ressure, hecto\$ascals h8a#, ρ is the air densit3 in I1m[&], R is the ideal 1as constant, >W^X mol^X and T is the tem\$erature in Velvin. (ince R varies 6 ith the de1ree o\$ humidit3, 7B. 4#, is used 6 ith the values !8) > V[&]I1[&] for dr3 air and 42' > V[&]I1[&] for 6 ater va\$our @, \$.8%A

$$R = (461 q) + (1 - q)287 \quad \text{4 \#}$$

To obtain B, the absolute humidit3 o\$ 6 ater va\$our I1 \$er I1 o\$ moist air the \$ollo6 in1 formula is used 6 here ".2! ' ' 8/! %# is the ratio o\$the e\$ective molecular 6 ei1hts o\$ 6 ater va\$our and dr3 air, @, \$. ' !) A

$$q = \frac{0.621 p_{wv}}{p_{atmos}} \quad , \#$$

p_{atmos} is the barometric readin1 at that moment in time for the three locations and p_{wv} is the \$artial \$ressure o\$ 6 ater va\$our, as calculated, at the same time o\$ readin1. P hen the value o\$: is a\$ \$1ied to 7B. 4#, it 1ives the value o\$ 1, the ideal 1as constant for moist air, as 6 ater va\$our is added or removed. r is the absolute humidit3 o\$ 6 ater va\$our in dr3 air, hence I1 o\$ 6 ater va\$our \$er I1 o\$ dr3 air. To obtain r , 7B. 2#, the absolute humidit3 for moist air, : , 1irst needs to be converted to the absolute humidit3 for dr3 air, r @, \$. ' !) A

$$r = \frac{q}{1-q} \quad \text{2 \#}$$

To calculate the s\$eci\$ic humidit3, ' 6 ater va\$our in 1rams \$er cubic metre o\$ moist air#, the values o\$ q and ρ the air densit3 in I1m[&] are reBuired, as are the values for 1, see 7B. 4# and ; , as derived from the e0\$erimental data.

The air densit3, ρ , in I1m[&] is obtained 7B.)#, usin1 the ideal 1as eBuation, see 7B. +#, 6 here the barometric \$ressure is 1iven in \$ascals 0a).

$$\frac{Pa}{RT} = \rho \quad \text{) \#}$$

The humidit3, ' , o\$ moist air, in 1rams \$er cubic metre 6 ill be obtained, 7B. 8, from the \$ro\$ortion o\$ humidit3, : , in a 1iven air densit3 ρ , as from 7B.)#.

$$h = q \rho 1000 \quad \text{8 \#}$$

7B. %# massYacceleration# \$rovides the I1netic ener13 values P \$# for chan1es in the \$artial \$ressure o\$ 6 ater va\$our, $\frac{\Delta Pa}{\Delta t}$, and that o\$chan1e in air densit3 \$er second, $\frac{\Delta \rho}{\Delta t}$. The 1ravitational constant, g , is tal en as %8' ms[&].

$$J \text{ or } W.s = 9.81 \frac{\Delta p}{\Delta t} m^3 \text{ and } J = \frac{\Delta Pa}{\Delta t} m^3 \quad \% \#$$

Usin1 7B. ' "#, the I1netic ener13 reBuired in circulatin1 all the enclosed air <# in the columns and connectin1 tunnels, some' %, m^+ , can be estimated from the average air densit3 at the time o\$ measurement and from the measured air velocit3. For e0am\$le, at an average air densit3, ρ , o\$' .! , I1 m[&], and a volume < o\$! " m^+ , the total mass o\$ air 6 ould be !, I1. P ith a velocit3, v , o\$ " .! ms[&], the I1netic ener13 reBuired 6 ould be " ., P \$ @A

$$W s = 0.5 \rho V_{total \text{ air}} v^2 \quad ' " \#$$

Trans\$ormin1 7B. ' " # into 7B. ' ' # \$rovides the means to convert the I1netic ener13 P \$# from the rate o\$chan1e o\$ air densit3 and o\$ \$artial \$ressure into average air\$1o6 velocit3 in the entire structure mass o\$ air a\$ \$ro0imatel3 ! , =g#

$$v^2 = \left(2 \frac{W s}{\rho V_{total \text{ air}}} \right) = \frac{W s}{12.5} \quad ' ' \#$$

As : c\$1lveen @, \$.44+A\$oints out, thermo\$1namical3, it is relativel3 strai1ht\$or6 ard to calculate the tem\$erature increase in each I1lo1ram o\$ air as condensation tal es \$1ace.

$$\Delta T = \frac{L m}{C_p} \quad ' ! \#$$

P here ; is Velvin; > is the latent heat o\$ va\$orisation o\$ 6 ater va\$our direct3 to ice, ! .%: > I1[&]; and C_p is the heat ca\$acit3 o\$ dr3 air at constant \$ressure, ' , " " " > I1[&]V[&].

: c\$1lveen 1ives the e0am\$le o\$' 1ram o\$ 6 ater va\$our condensin1 into liBuid 6 ater and sho6 s that it 6 ill 6 arm ' I1 o\$ air b3 ! , JC. a substantial amount.

The condensation o\$ 6 ater va\$our leaves the remainin1 air denser, 6 hich combined 6 ith its e0\$ansion into the \$artial vacuum from condensation causes the tem\$erature to decline. The relationshi\$ bet6 een tem\$erature chan1e and air densit3 chan1e is as \$ollo6 s @A\$.444.

$$\Delta T_v = 0.621 \Delta q T \quad ' + \#$$

P here T_v is the virtual tem\$erature o\$ the 6 ater va\$our; T is the actual tem\$erature o\$ the air; and : is the s\$eci\$ic humidit3 o\$ moist air, I1 6 ater va\$our \$er I1 moist air. For the condensation o\$ one 1ram o\$ 6 ater va\$our in ' I1 o\$ air at " JC, the tem\$erature reduction 6 ould be " . ') JC.

. ! he conce"t o\$ air "arcel\$

*n this \$a\$er, the term 1air \$arcelM is used to describe the volume o\$ the 1a\$er o\$ air in\$uenced b3 the coolin1 elements as it \$asses over them see H1. ' 9#. As indicated belo6 , \$arcel si\$e is determined b3 the condensate collected as rain at the conclusion o\$ each e0\$eriment.

*n all the e0\$eriments, a vertical air\$1o6 u\$6 ards or do6 n6 ards# 6 as observed 6 ithin + " seconds a\$ter the coolin1 elements 6 ere s6 itched on and condensation be1an to tal e \$1ace. The Buestion here is ho6 to calculate the

volume o5 air as it \$asses u\$ or do6 n throu1h the coolin1 elements durin1 one second Z Tiven that the len1th o5 tubin1 5ormin1 the coolin1 elements is ') . " + m and the diameter o5 the coils is " . " ! m, the sur\$ace area o5 the coolin1 elements is " .24! m². *n order to derive the volume, that sur\$ace area must be multi\$lied b3 the e\$ective e0tension o5 coolin1. 9 3 Ino6 in1 the total Buantit3 o5 condensate 1athered at the conclusion o5 each e0\$eriment, the averse volume o5 air that \$asses over the coolin1 elements durin1 each second can be calculated.

Hrom 7 B. , #) # = 8#, the absolute humidit3, : , at , s intervals# in I1/I1 moist air can be calculated 5or the air at the coolin1 coils and 5or the air 0e0t in lineK as can the air densit3, ρ , I1m³ o5 moist air, and 5nal13 the humidit3, ' , in 1m³. 9 3 subtractin1 the humidit3, ' , o5 the air at the coolin1 coils 5rom the humidit3 o5 the air ne0t in line, the result 6 ill be 1m³ o5 6 ater va\$our 6 hich 6 ill have condensed over the , s interval bet6 een one measurement and the ne0t. 9 3 a11re1atin1 the di\$erence in ' 5or each measurement over the entire e0\$eriment, the total loss o5 6 ater va\$our to condensation \$er second can be calculated as i5 the coolin1 volume 6 ere' cubic metre in si?e. That volume, ' m³, 6 ill e0ceed b3 a \$actor, @ the actual volume si?e o5 the \$arcel blocI that is \$assin1 over the coils. Therefore, the total condensate, c, as measured 5rom the \$reci\$itate, multi\$lied b3 @ 6 ill be eBual to the a11re1ate o5 6 ater va\$our condensed, ' @ 1m³#, the \$actor, @ bein1 the number o5 times the actual blocI si?e divides into ' m³. (ince the sur\$ace area o5 the coils is " .24! m², the \$actor @ 6 ill be ' / " .24! e#, 6 here e# is the averse e\$ective la3er, 7 B. ' 4.

$$ef = \frac{1}{0.642 x} \quad ' 4 \#$$

Hrom the data, ' @ 1m³# can be obtained 7 Bs. ! #&0%, and Ino6 in1 the actual Buantit3 o5 condensate, c, 7 B. ' , # 6 ill live \$actor @

$$x = \frac{h_x}{c} \quad ' , \#$$

The e\$ective la3er, e#, is 5ound to lie bet6 een " . " 4 m and " . " 8 m 5or di\$erent e0\$eriments, the di\$erence bein1 a conseBuece o5 the air\$oe velocit3. De\$endin1 on the e0\$eriment, the averse \$arcel volume \$er second varies 5rom " . " + m³ to " . " 2 m³ H1s.) , 8#. As both H1.) , 8 sho6 , the curve o5 the a11re1ated condensation o5 6 ater va\$our a1ain\$ time 5ollo6 s a near \$tra1ht line 6 ith an 1² o5 " . % , thereb3 \$rovidin1 4usti\$ication 5or 7 B. ' 4#& , #.

\$. Results

The 6 idel3 & acceted assum\$tion is that the movement o5 air in condensation o5 6 ater va\$our is invariabl3 an isotro\$ic \$rocess, 6 ith the air movin1 5rom all directions simultaneousl3, \$reventin1 an3 net, uni\$irectional \$oe6 . The e0\$erimental results indicate instead that condensation can be anisotro\$ic, and can lead to net air\$oe . *sotro\$ic condensation is inherentl3 unstable, 1iven the im\$robabilit3 o5 eBuivalent conditions e0istin1 in all \$lanes surroundin1 the

\$oint o5 condensation.

*n all e0\$eriments, once re\$ri1eration 6 as s6 itched on, air\$oe became a\$arent 6 ithin + " seconds, throu1h movement o5 the 1au?es, around the entire ' 4 m internal len1th o5 the structure.

H1s. ! , + sho6 a clocI 6 ise air\$oe , correlated 6 ith the \$eriods o5 re\$ri1eration and 6 ater va\$our condensation.

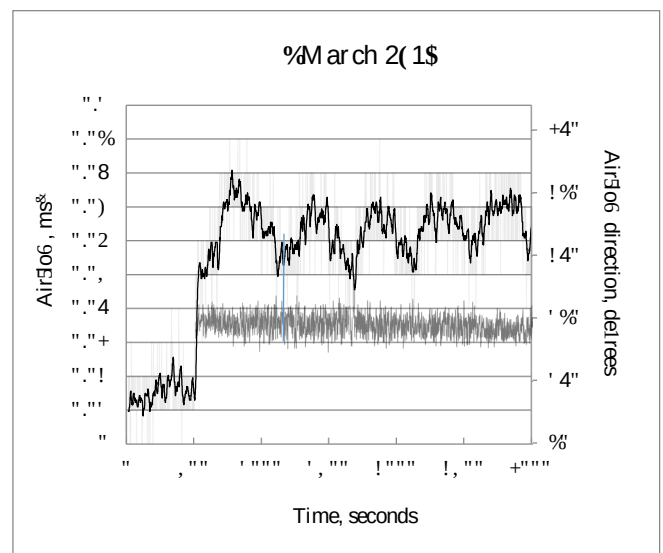
H1. 4 sho6 s a similar e0\$eriment, a1ain 6 ith no internal heatin1. 9 ut on this occasion, the ri1ht column 6 as observed to be ' [C 6 armer than the le\$, and the air had a sl1ht counter\$locI 6 ise \$oe6 . P hen the coolin1 6 as s6 itched on and o5 , in 5our c3cles, the associated air\$oe s 6 ere observed 5rom the 1au?es and anemometer to be counter\$locI 6 ise.

The \$eriods o5 coolin1 in H1. 4 corres\$ond to the rise and 5all in the rate o5 condensation. The times o5 coolin1 are on at +4, s, ' ! 4" s, ' + " s, + " " s and o## at 2+ " s, ' , + " s, ' 44" s, +4% s. At a\$ \$ro0. %2" s, the air\$oe sho6 s a short&lived \$eal o5 " . ") ms² 6 hich should be com\$ared 6 ith the " . ! & " . ' 4 ms² lon1er&lived \$eal at ' , ' " s. A doublin1 o5 air\$oe circulation demands a 5our\$old increase in 1inetic ener13; " . " 2' ! , P s com\$ared to " . ! 4, P s.

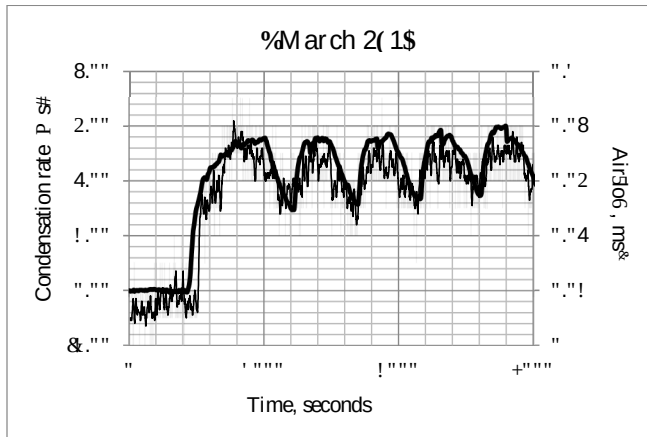
H1. , 2 both sho6 the same e0\$eriment o5 + " >anuar3 ! " " 2, 6 ith the coolin1 tubes s6 itched on and o5 \$eriodical3, but 6 ith the heatin1 mat on throu1hout. The \$oe6 o5 air 6 as counter\$locI 6 ise le\$6 ards in the to\$ tunnel# - n account o5 directionalit3 at the anemometer oscillatin1 bet6 een around ' J or +2" J, the 1ra\$h sho6 s a series o5 vertical lines.

% E&\$eriments' eri#ying air " arcel conce"t

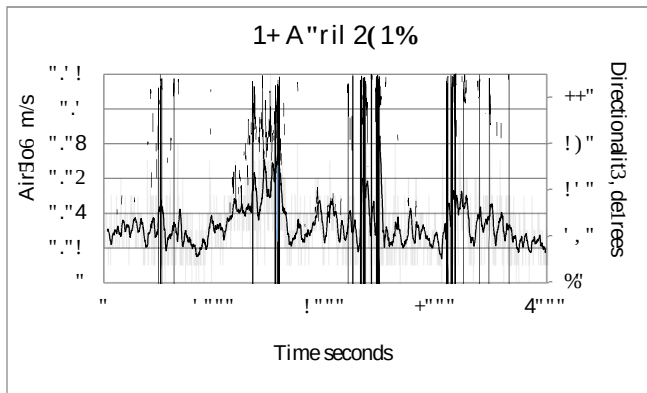
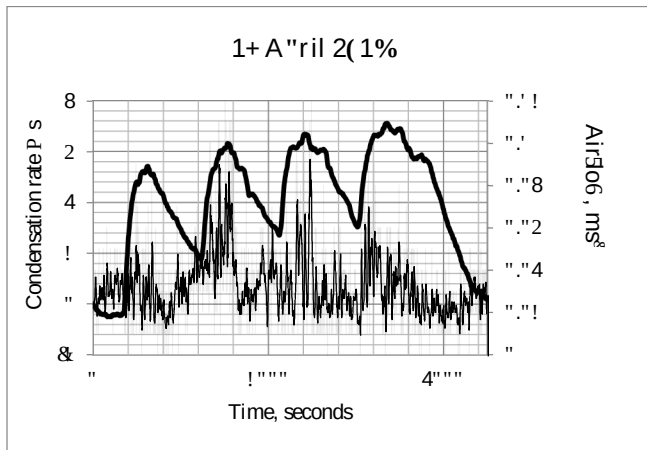
The air \$arcel conce\$t, described in : ethodolo13, enables the derivation o5 the rate o5 condensation, and the rate o5 an increase in air densit3 as a result o5 the air becomin1 simultaneousl3 more dense and cold. The calculation de\$ends on a \$arcel o5 air 6 ith an averse volume o5 bet6 een



H1ure ! . 6 * arc' 24(A. The u\$ser curve, le\$ and a0is# 6 ith its \$eal s, sho6 s air\$oe \$seed, and the line a ' , \$econd movin1 averse. The horiZontal curve sho6 s air\$oe direction. Hve c3cles o5 s6 itchin1 re\$ri1eration on and o5 , 6 ith corres\$ondin1 \$eal s in air\$oe o5 u\$ to " . " % ms². The air\$oe 6 as clocI 6 ise, at around ' 8" J. (ource. 9 un3ard



H1ure +. 6 * arc' 24(A The u\$ser curve sho\$ s the rate o\$ chan1e o\$ the \$artial \$ressure o\$ 6 ater va\$our \$ \$6 v# at the coolin1 coils, converted to P att.seconds 1e3/hand a0is#. As before, the 411ed curve sho\$ s air\$06 \$seed as a '1\$econd movin1 averate. 9eauce o\$ lo6 e0ternal tem\$eratures, the com\$ressor thermostat automaticall3 s6 itched the re\$ri1eration on and o\$ The \$ro\$le o\$ the rate o\$ decrease in \$ \$6 v sho\$ s \$eal scores\$ondin1 6 ith \$eal sin the docl 6 ise air\$06 ms\$. (ource. 9 un3ard

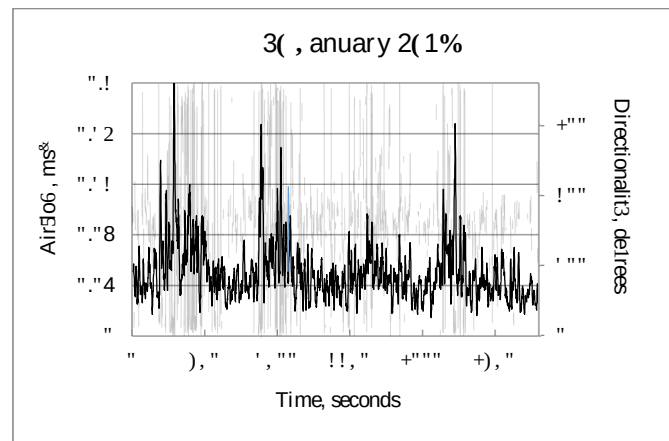


H1ure 4. 19 April 2016. The u\$ser 1ra\$h and u\$ser curve sho\$ s the rate o\$ chan1e o\$ the \$artial \$ressure o\$ 6 ater va\$our \$ \$6 v# at the coolin1 coils, converted to P att.seconds; the 411ed curve sho\$ s air\$06 \$seed, as a '1\$econd movin1 averate. Air\$06 6 as observed to be u\$6 ards over the coolin1 coils and therefore counter& docl 6 ise. Air\$06 \$eal s 6 ere associated 6 ith the \$eal s o\$ the \$artial \$ressure chan1e P s#. No artifi\$ial heatin1 6 as a\$ \$lied, 3et the tendenc3 throu\$out 6 as for the air in the ri1ht column to move u\$6 ards a\$ \$ro0. " " ! ms\$. The lo6 er curve sho\$ s the air\$06 and directional\$3, in this case counter& docl 6 ise. The air\$06 \$eal s correlate 6 ith counter& docl 6 ise directional \$06 circa' " " and +, "J# (ource. 9 un3ard

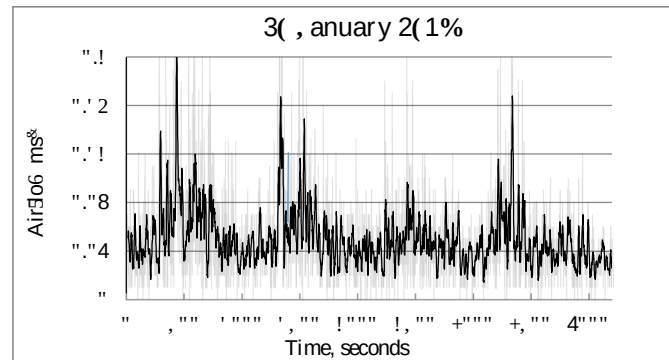
"." + m+ s& and "!", m+ s&, as calculated and contin1ent on the individual e0\$eriment; see 7B '4# ', # H1.), sho6 in1 accumulated condensate, is obtained usin1 the \$actor 0 to convert the all related total o\$ h0 from ' m+ do6 n to the volume si?e o\$ the \$arcel o\$ air, namel3 "!", m+ s&. 70\$eriments 6 ith air\$06 o\$ "!" ms& or less, H1.)# tend to 6 ards the smaller \$arcel si?e o\$ "!" + m+ s&; e0\$eriments 6 ith air\$06 o\$ "!" ms& tend to 6 ards the higher virtual \$arcel si?e o\$ "!" 2 m+ s&, as sho6 n in H1. 8.

). * atent heat

The 6ides\$read scientifi\$ assumption is that the movement o\$ air is isotro\$ic, 6 ith cancellation o\$ an3 net \$06. The e0\$eriments indicate that condensation can be anisotro\$ic, tri11erin1 a net, uni& directional \$06. 9ut the \$otential role o\$ latent heat in air circulation nevertheless needs e0\$lorin1. *n the e0\$eriment sho6 n in H1. %o\$ + " " " / " " " 2, 6 hen the re\$ri1eration 6 as s6 itched



H1ure, . + " >anuar3 ! " " 2. The black curve sho\$ s air\$06 \$seed as a '1\$econd movin1 averate \$eed and the vertical, 1re3 lines the direction o\$ air\$06. P ith the heatin1 8nat s6 itched on throu\$out, 5our c3des o\$ re\$ri1eration 6 ere carried out, 6 ith " " minutes bet6 een each 6 ith the re\$ri1eration s6 itched o\$5. Counter& docl 6 ise air\$06 increased durin1 the \$eriods o\$ coolin1 and subsided durin1 the \$eriods bet6 een. The directional\$3 sho\$ s \$uctuation bet6 een " " J and +, "J. (ource. 9 un3ard



H1ure 2. ?4 Ban 'ar! 24(6 same e0\$eriment as H1. , # The vertical, 1re3 lines sho\$ s air\$06 \$seed, and the black curve a '1\$econd movin1 averate. P ith the heatin1 8nat s6 itched on throu\$out, 5our c3des o\$ re\$ri1eration lastin1, 6 minutes each 6 ere carried out, 6 ith " " minutes bet6 een each 6 hen the re\$ri1eration 6 as s6 itched o\$5. Counter& docl 6 ise air\$06 increased durin1 the \$eriods o\$ coolin1 and subsided durin1 the \$eriods bet6 een. The directional\$3 as seen in H1. , has been removed. ; o6 ever, the vertical lines o\$ the air\$06 can be com\$ared and matched 6 ith the directional\$3 lines o\$ H1. , . (ource. 9 un3ard

on, the air temperature at the cooling coils was immediately reduced, indicating that the latent heat released by water condensation was fully absorbed by the cooling tubes. Moreover, as refrigeration continued, with the temperature dropping so as to increase the rate of condensation, the associated increase in latent heat released per second did not show up as a leveling off of the temperature decline. Latent heat release thus cannot account for the upward slope as shown in Fig. 4. Indeed, for it to be available for work, it would counter the downward slope as in Fig. 1, 2, 3. The potential energy driving air flow in the condensation model must therefore come not from latent heat, but from partial pressure change. It is important to convert $7B \cdot \frac{1}{2}$ to P through dividing by C_p , the heat capacity of dry air at constant pressure, namely $\frac{1}{2} > 1.1 \frac{1}{2}$.

Fig. 1 shows a significant correlation and regression $R^2 = 0.94$, a value just between air flow and the inverse pressure change from condensation. This is also consistent with the condensation model as an explanation of air flow. Finally, experiments with the anemometer placed more than 1 m away from the cooling coils and in the centre of cross-sectional area of the upper tunnel indicate that air flow is not limited to a thin stream but encompasses at least one third, if not all, the internal space of the structure. In one experiment, Fig. 1, 2, 3, 4, is shown with clockwise circulation. The initial refrigeration air flow is clockwise, amounting to approximately 0.2 m³/s. Within 10 seconds of the refrigeration being switched on, the air flow, clockwise, has doubled to 0.4 m³/s and the rate of condensation from 0 to 0.8 P/s.

Discussion

This paper is the result of more than 10 experiments, carried out between 1994 and 1999, held under different internal atmospheric conditions and analysed using conventional physics. The kinetic energy contributions from the partial pressure change in water vapour during condensation and from the air density change at the cooling coils are displayed in Table 1 for 10 different experiments. The cross-sectional area encompassed by each layer of the cooling coils is one third the cross-sectional area of the column. Therefore, the kinetic energy to move one third of the total volume of air contained in the structure is calculated on the basis of the anemometer reading. The direction of air flow, whether clockwise or counter-clockwise, is always consistent with anisotropic condensation. As Table 1 shows, the potential energy from partial pressure change is more than adequate to account for the kinetic energy of observed air flows, while the potential energy from cooling the same portion of air and accounting for density change, in general, falls short by a factor of 10 or more. Furthermore, the air density change per second shows no correspondence with the sea level air velocity, thus indicating it cannot be responsible for the air flow, whether clockwise or anti-clockwise.

In the experiment of 1999, with the anemometer more than 1 m away from the cooling elements, significant air flow is detected throughout. Judiciously placed cameras focussed on horizontal tubes, indicate that the change in the partial pressure of water vapour during the cooling cycle is sufficient to bring about convection throughout the entire structure, Fig. 1.

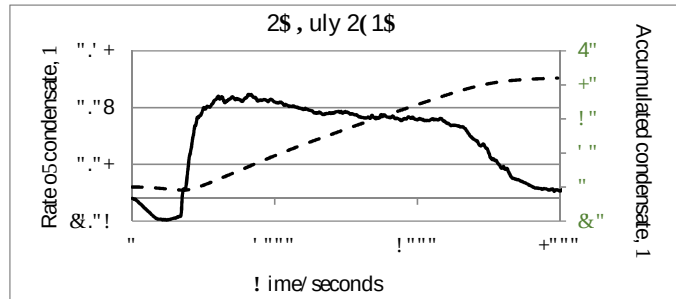
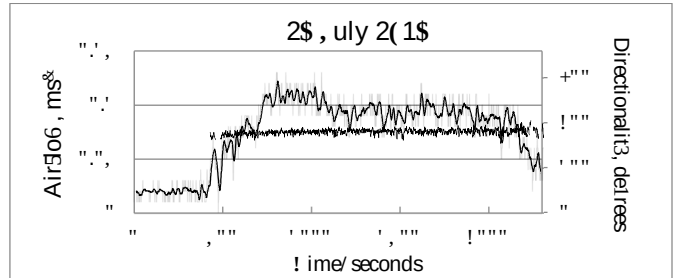


Figure 1. 2A B 1 24(A. In the upper graph the upper curve shows air flow speed, as a 1-second moving average, and the horizontal curve shows air flow direction, in this experiment, clockwise. In the lower graph, the left-hand axis shows the dynamics of the rate of condensation in 1/s and the right-hand axis, with the dotted curve, shows its accumulation. Refrigeration was switched on at 10 seconds and off at 40 seconds. The quantities collected and plotted from the rain troughs as 1, 6 high, 6 high as listed to give the average size of the air underpinning refrigeration 0.2 m³/s through using 7B · 1/2, # resulted in an accumulated condensation of 1.1 see Concept of Air 8 arc. The slope of the accumulated condensate during the refrigeration has an 1.2×10^{-3} %).

(Source: 9 un3ard)

Neither air density changes nor latent heat release, whether the flow is clockwise or counter-clockwise, can explain the enhanced air flow as observed in all experiments undertaken @A 7B · 1/2 conforms to the kinetic energy required to account for the rate of change in the partial pressure of water vapour. That kinetic energy required by the air surrounding the locus of condensation is considerably more than that required to generate air flow around the structure as 0.1 m³ cubic metres of air, the assumption being that some is taken up in isotropic condensation and the remainder in anisotropic condensation, with sufficient power to overcome friction and turbulence. The position of the tubes, with observation of their movement, and the anemometer, indicate that a convection cycle is generated.

7B · 1/2 is critical in terms of explaining how the relative energy of partial pressure reduction transforms into a temperature change relative to high, high multiplied by C_p , the heat capacity of dry air, some $\frac{1}{2} > 1.1 \frac{1}{2}$, gives the values equivalent calculated for the change per second in the condensation rate converted into P/s.

Interpreting the experimental results in terms of the atmosphere at large requires caution, but they do suggest that the mightiest intense condensation occurs, especially in and above closed moist forest, in the tropics year-round and in temperate zones in summer. 7B · 1/2, being fundamental to the physics of ideal gases, is inevitably as valid in the atmosphere at large as it clearly does in the experiments.

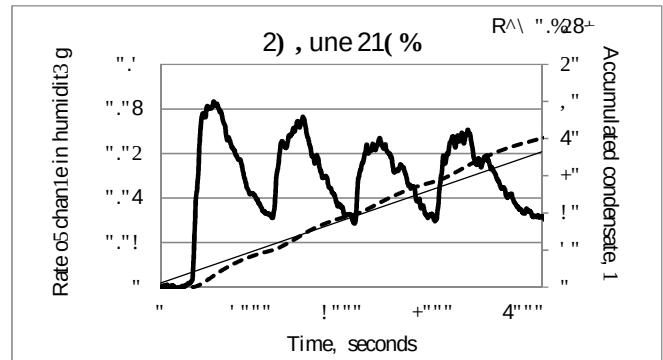
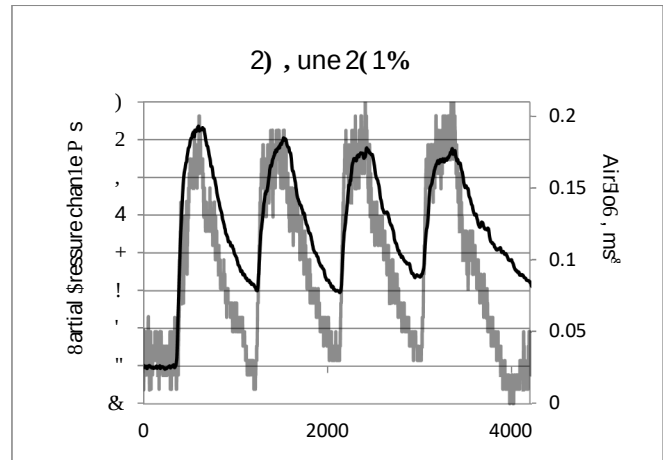
Table'

V7 characteristics o5 e0\$erimental data.

. ate # e&\$eriment	0 ea1 air/ ms ²¹	. irection air #low: anti2 cloc1wise 3A4 56 cloc1wise 3A5	0 ea1 "artial "ressure change 7 s	0 ea1 air density change 7 s	8 inetic energy #or one2 third total 'olume o# air/ 7 s
" ! / ") / ! " " ,	" . " 8	AC	, .	" . " " 4	" . " " 12
" 2 " " + ! " " ,	" . " %	C	4 !	" . " " + !	" . " " + +
" 8 " " ! / ! " " ,	" .	C	, . +	" . " " " 2	" . " 4
! 2 " " , / ! " " 2	" .	C	% ! 4	" . " ") 8	" . " 4
' 4 " " / ! " " 2	" .	C	4)	" . " " " + 8	" . " 4
! , / ") / ! " " ,	" .	C	) . 2	" . " " , 4	" . " ,
" " / ") / ! " " ,	" .	AC	%	" . " ")	" . " ,
! 2 " " 4 / ! " ")	" .	AC	,	" . " " 2	" . " ,
' ' / " 4 / ! " ")	" . !	AC	4 !	" . " " 48	" . " 2
" + " " , / ! " " 2	" . !	AC	% !	" . " " 28	" . " 2
" 8 " " , / ! " ")	" . +	AC	4)	" . " " ,	" . " ,
' + / " " / ! " " 2	" . +	C	2	" . " " " +	" . ")
' % " 4 / ! " " 2	" . 4	AC	2	" . " " ,	" . " 8
" " / " 4 / ! " " ,	" . 4	C	, . , +	" . " " 4	" . " 8
" " / " ! / ! " " ,	" . 4	C	4 ")	" . " " ! ")	" . " %
+ / " / " / ! " " 2	" . 4	C	2	" . " " " +	" . " 0
") / " 4 / ! " ")	" . ,	AC	! !	" . " " !	" . " %
+ " / " 4 / ! " " 2	" . ,	AC	2 %	" . " " 2	" . " %
!) / " 2 / ! " ")	" . 2	C	)	" . " " ,	" . " ,
' 4 " " / ! " " 2	" . 2	C	) . 8	" . " " 2	" . " ,
!) / " 4 / ! " ")	" . 2	AC	4	" . " " 2 +	" . " ,
! 8 " " ! / ! " ")	" . 2	AC	,	" . " " 4	" . " ,
! 4 " " / ! " ")	" . 2	AC	) . 42	" . " " ! 2	" . " ,
' % " " / ! " ")	" . 2	AC	) . ! ,	" . " " " + 2	" . " ,
" % " 2 / ! " " 2	" . 2	C	% 8	" . " ") ! ,	" . " ,
" 8 " " / ! " " ,	" . 2	C	8 :)	" . " " 2 ,	" . " ,
' , / " / ! " " ,	" . 2	C	! ,	" . " " " %	" . " ,
" " / ") / ! " " 4	" .)	AC	) .	" . " " 2	" . " !
' , / " % ! / ! " " 4	" .)	C	8	" . " " 4	" . " !
! , / " " / ! " ")	" .)	AC	) . !	" . " " 24	" . " !
!) / " + / ! " ")	" . 8	AC	2 . 8	" . " " 4 !	" . " + +
" 4 " " + / ! " ")	" . 8	AC	2 %	" . " " ,	" . " + +
" % " " / ! " ")	" . 8	AC	4 ,	" . " " 4	" . " + +
' + " " / ! " ")	" . 8	C	, .) ,	" . " " + +	" . " + +
" + " " + / ! " " ,	" . 8	C	+ 2	" . " " ! 8	" . " + +
" 4 " " 8 / ! " " ,	" . 8	C	) . !	" . " " , 2	" . " + +
' % " " / ! " " ,	" . 8	C	+ + 2	" . " " " +	" . " + +
" + / " ! / ! " " ,	" . 8	C	2	" . " " 4	" . " + +
! " / " " / ! " ")	" . %	AC	4 ,	" . " " " + 4	" . " 48
! " / " / ! " " ,	" . %	C	+ , .)	" . " " 4 ,	" . " 48
') / " % ! " " ,	" . %	C	+ , . !	" . " " , 4	" . " 48
" " / " ! / ! " " 2	" . !	AC	4	" . " " 4	" . " 2 ,
+ " / " " / ! " " 2	" . !	AC	4 ,	" . " " " +	" . " 2 ,
" " / " , / ! " ")	" . !	C	4 . 2	" . " " + 2	" . " 2 ,
!) / " 2 / ! " " 2	" . !	C	2 . 4	" . " " ! +	" . " 2 ,
! + " " / ! " ")	" . !	AC	2 ,	" . " " 48	" . " 8
" 4 " " / ! " " 4	" . ! !	C	+ ,	" . " " 42	" . " !
" 2 " " 8 / ! " " ,	" . ! !	C	) . !	" . " " 44	" . " !
! ! / " % ! " " ,	" . ! !	C	2 . 8	" . " " 4 %	" . " !
' 2 " " % ! " " ,	" . ! !	C	+ 2	" . " " 22	" . " !
" " / " " / ! " " 2	" . ! +	AC	"	" . " " 24	" . " ! !

(ource. 9 un3ard

The conventional \$oint o5 vie6 is that the I inetic ener13 for convection derives from the 1eneral \$rinci\$le that hot air rises and cold air sin1 s . ; o6 ever, as : al arieva et al. @A \$oint out, 6 hen hot air rises in the lo6 er atmof\$here it cools because o5 e0\$ansion and 6 hen the same, but no6 cooler, air sin1 s it heats u\$, such that the overall 1ain or loss in I inetic



H1.8. 2) B ne 24(6. The u\$er 1ra\$h sho\$ the air\$6 over 4 re\$iteration c3cles 4a1led bla\$ # and the \$artial \$ressure chan1e in 6 ater va\$our u\$er curve, P s#. The lo6 er 1ra\$h sho\$ the chan1e in humidity3 \$eal ed u\$er curve, 1# and the a1l related accumulation o5 6 ater va\$our dashed # throu1h usin1 7 B. ' 4# ' , # and a volume si?e for the air \$arcel o5 " . " 2 m". The slo\$e o5 the accumulated condensate durin1 re\$iteration has an 1 " o5 " % . (ource. 9 un3ard

ener13 is ?ero. The same coolin1 and heatin1 ha\$ \$ens 6 hen air e0\$ands and 5orces air el\$e here to com\$ress; there is no net ener13 1ain to do 6 or 1. *n other 6 ords, a strict a\$ \$lication o5 the 5rst 1a6 o5 thermodynami\$ to the atmof\$here 6 ould 3ield a rate o5 I inetic ener13 1eneration e\$ual to ?ero. *n that re\$ect, the buo3anc3 5rom latent heat release 6 ill be counteracted b3 cold air 5rom above sin1 in1, thus 1eneratin1 a h3drodynami\$ e\$uilibrium.

Accordin1 to the 98T @A@A, rain\$ore\$ts, 3ear&ound in the e\$uatorial tro\$ics and durin1 the summer in boreal relions, 5eed the lo6 er atmof\$here 6 ith 6 ater va\$our, u\$ to + \$er cent o5 atmof\$heric \$ressure, and thereb3 \$rovide the source material 5or cloud condensation. The de\$letion o5 6 ater va\$our and the resultin1 rarefaction o5 the local atmof\$here in the localit3 o5 condensation cause convection over the 5orest, accordin1 to the 98T. From that \$oint o5 vie6 , it is the h3drolo1ical c3cle, includin1 6 ater eva\$oration and condensation, 6 hich drives convection and there\$ore the circulation o5 the air masses. That is in shar\$ contrast to the orthodo0 vie6 o5 convection and air mass circulation, 6 hich ar1ues that the movement o5 the air mass drives the h3drolo1ical c3cle throu1h latitudinal di\$ferences in tem\$erature, hel\$ed on b3 the buo3anc3 1enerated as a result o5 the release o5 latent heat @ \$. 444A

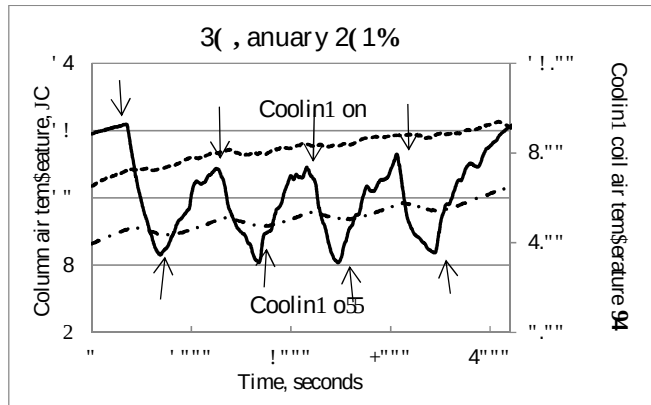


Figure 24(B). Air temperature at the cooling coils, the dotted curve the temperature in the mid-right air column below the cooling coils, and the dashed curve the temperature in the lower left air column. The heating material is on throughout four successive refrigeration cycles, with the on and off times shown by vertical arrows. The temperature decline on refrigeration indicates that the latent heat was annulled and could not be the cause of the enhanced upward air circulation shown in Figure 24(A). (Source: 9 un3ard)

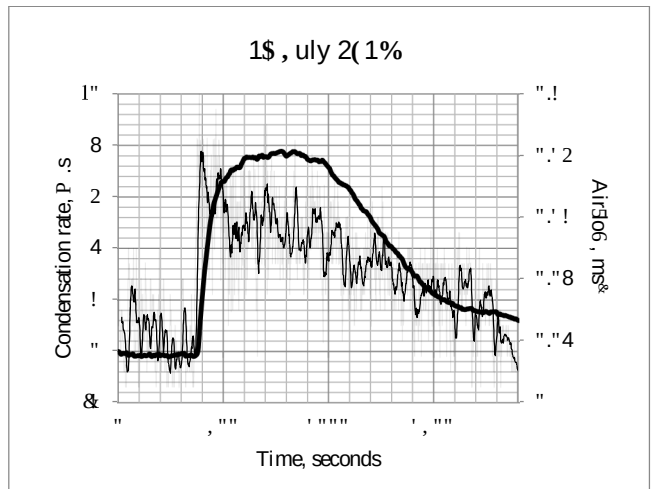


Figure 24(C). In this experiment shown in clockwise air flow, the anemometer is placed immediately from the cooling elements. The initial sharp rise in air flow at 1000 s followed curve is matched by a sharp rise in the condensation rate (solid curve). (Source: 9 un3ard)

The proposition that a high rate of evapotranspiration from forested regions is a prime mover of major air mass convection remains contentious: eesters et al. (2007) are affected the 98T on the grounds that the ascending air motions induced by the evaporative/condensation force could rapidly restore hydrostatic equilibrium and thereby become extinguished. In reply: alarieva et al. (2007) pointed out that condensation removed water vapor molecules from the mass phase and reduced the weight of the air column. That removal must disturb hydrostatic equilibrium and make air circulate under the action of the evaporation/condensation force.

In effect, the 98T states that the major physical cause of moisture fluxes is not the nonuniformity of atmospheric and surface heating, but that water vapor is invariably used and directed as a result of the rarefaction of air from condensation (Alarieva et al., 2007).

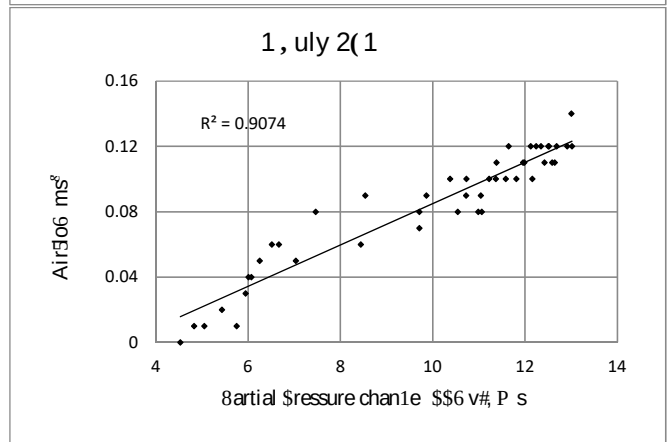
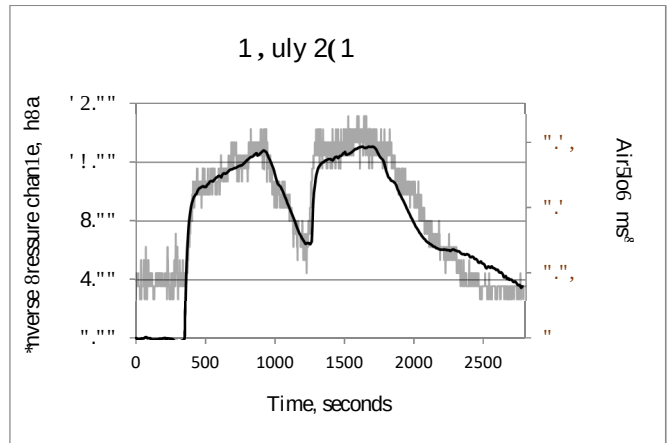


Figure 24(D). In the upper left the dashed line curve shows air flow speed and the black solid curve the inverse rate of channel in P.s. The clockwise air flow right axis shows a close correspondence to the condensation rate left axis. The lower left shows the significant correlation $r^2 = 0.9074$ (p-value 74.44%, Pearson's Coefficient 4.52) between air flow and partial pressure channel. (Source: 9 un3ard)

7 evidence in favour of the 98T has come from a number of different sources: alarieva et al. (2007) are affected to data shown that precipitation over river basins which are covered in forest remains as high in the deep interior of the continent as at the coast, whereas river basins without forest show an exponential decline in rainfall as one passes from the coast inland. (Sracilen et al., 2007) have shown from their recent statistical study of rainfall and land cover, as indicated by the leaf area index (LAI), that satellite-derived rainfall measurements are positively correlated with the degree to which model-derived air trajectories have been exposed to forest cover.

8 oveda et al. (2007) provide evidence that when the low level jet streams pass over forested regions precipitation levels stay high and constant, whereas over regions which lack forest, precipitation levels decline exponentially, just as the 98T suggests should happen. 8 oveda and his colleagues look at the low level Chocó jet and comment that the channel in direction of the Pacific Austral Trade Winds from Easterlies to Easterlies just over the Equator at 4°N, may be their abrupt switch to the unsaturated degree of evapotranspiration and subsequent condensation over the Chocó in Colombia.

P ith more than +8", "" cubic metres\$er second o56 ater va\$our brouht in from the Tro\$ical Atlantic - cean, the Ama?on 9asin 5unctions on a 5ar 1rander scale than the ChocD@+A *t 6 ould a\$5ear that eva\$otrans\$iration rates are su\$icientl3 hi1h over the rain5orest to increase the volume o5 the Ama?onian atmos\$heric river in the 5orm o5 the (outh American Co6 Ceval >et (tream as it a\$5roaches the 6 estern reaches o5 the Ama?on 9asin and is then de\$ected both u\$6 ards and south6 ards on encounterin1 the Andes @4A

93 5ocussin1 on tem\$erature chan1e rather than the \$ressure chan1e 6hen condensation occurs in the atmos\$here, the latent heat release and subseBuent air 6 armin1 is deemed to more than com\$ensate 5or the small reduction in tem\$erature from the air e0\$andin1 into the \$artial vacuum, 7B. ' !# ' +# ; o6 ever, the 98T tal es into account the rare5action o5 the atmos\$here and the \$ressure chan1e as 6 ater va\$our condenses.

: oreover, in the e0\$erimental set&u\$ latent heat release is eliminated b3 means o5 re5ri1eration and 3et air5o6 alain\$ 1ravitational constraints is measurabl3 enhanced as seen in Table' AC#and from Hi1. 4 = , . That 5indin1 leaves \$artial \$ressure chan1e from condensation as an im\$ortant candidate 5or causin1 air5o6 and it raises 5undamental Buestions concernin1 the su\$posed isotro\$3 o5 air5o6 to the locus o5 condensin1 6 ater va\$our.

This \$a\$er describes an attempt to stud3 the \$h3sics in a laborator3 settin1. The results have been si\$ni5icant and unamb1uous. At the laborator3 scale, usin1 conventional \$h3sics such as is em\$lo3ed in climatoloical studies, the \$rimar3 5orce drivin1 convection a\$5ears to be the 1inetic ener13 o5 im\$lodin1 air as 6 ater va\$our condenses, 6 ith a sudden reduction &U !'"" &old &in the air volume o5 one 1ram&molecule o5 6 ater va\$our ' 8 1# as it transforms to liBuid and ice. ; ence, as air e0\$ands into the \$artial vacuum resultin1 from the condensation o5 6 ater va\$our it tal es u\$ heat from its surroundin1s 6 ich, to 1ether 6 ith the release o5 latent heat and the virtual 6 armin1 o5 air, maintain the conservation o5 ener13. Hurthermore, because o5 \$h3sical di5erences above and belo6 the re5ri1erated coolin1 coils, the \$rocess o5 eliminatin1 the \$artial vacuum is anisotropi\$ 6 ith the net result that condensation leads directl3 to uni&directional air5o6 .

+. 4 onclusions

The e0\$eriments described in this stud3, includin1 those sho6 n in Table' , indicate that air densit3 chan1es around the coolin1 coils are insu\$icient b3 more than an order o5 ma1nitude to brin1 about the observed air5o6 s, and that more than su\$icient \$otential ener13, bound u\$ in the \$artial \$ressure chan1es o5 condensation, is available to account 5or those same air5o6 s. *n the e0\$erimental set&u\$ at least, both latent heat release and air densit3 chan1es from the re5ri1eration can be ruled out as the cause o5 the consistent uni&directional net air5o6 s. Anisotropi\$ air5o6 to the locus o5 condensation remains the onl3 candidate, in contrast to the acce\$ted do1ma that isotro\$ic condensation is the norm and 5or 6 ich there is no evidence. *n e5ect, the tri11er 5or such directed air5o6 s derives from distinct ed1e conditions in the vertical \$lane, above and belo6 the area o5 condensation.

The laborator3 demonstration o5 anisotropi\$ condensation in causin1 enhanced air mass convection has im\$lications 5or climate modelers 6 ho ma3 have ne1lected this \$h3sical \$henomenon in 1eneratin1 their climate al1orithms. : an3 climate models ma3 need revision. And it 6 ould stronl3 su11est that the 1reat 5orests o5 the 6 orld \$la3 a 5undamental role in air mass circulation throuh \$rovidin1 6 ater va\$our via eva\$otrans\$iration, and in brin1in1 rain to the dee\$ interior o5 continents @, A@2A

Ac1nowledgements

The e0\$erimental structure 6 ith its eBui\$ment and the actual e0\$erimentation made \$ossible throuh the bounteous su\$5ort o5 the Tood 7nerlies Houndation, (6 it?erland. : an3 than1s to ; arr3 Hearnle3 5or his careful scrutin3 o5 the manuscri\$t. Hinall3, 6 e o6 e a \$ro5ound debt to >on Tini er 5or his hel\$ in the 6 itin1 o5 the manuscri\$t and his 5ersistent Buestionin1 o5 the methodolo13 and conclusions.

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, \$timi3ation models 4or \$o5 er s2stems in the evolution to smart 0rids- A revie5

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Abstract

The \$resent \$a\$er aims to describe the o\$timi3ation models recentl2 a\$lied to the desi0n and o\$erati0n o4 \$o5 er s2stems in the road to the 4ormati0n o4 smart 0rids and to identi42 the trends, challenges and \$ossible 0a\$ses e\$isti0n in this 4eld o4 stud2. The models described allo5 \$er4ormi0 o\$timi3ati0n o4 the desi0n and o\$erati0n o4 \$o5 er s2stems consideri0 as\$pects as rene5 able ener0ies and its related variabilit2, distributed 0enerati0n and micro 0rids, demand&site mana0ement and ener02 stora0e s2stems. Conclusions0oint out that several o4 the models recentl2 4ormulated need to be validated 5ith real data and lar0escale s2stems tests. 7 oreover, demand&site mana0ement and micro 0rids are as\$pects that lac; o4 the develo\$ment o4 complete o\$timal \$o5 er 4o5 models. <inall2, the accurate 4orecasti0n o4 stochastic variables is necessar2 to accom\$lish a better ada\$ti0n o4 models to real behavior o4 the \$o5 er s2stem.

%& ords- o\$timi3ati0n; rene5 able ener0ies; smart 0rids; o\$timal \$o5 er 4o5.

7 odelos de o\$timi3aci0n \$ara sistemas de \$otencia en la evoluci0n hacia redes inteli0entes- Una revisi0n

Resumen

>I \$resente art9culo describe los modelos de o\$timi3aci0n recientemente a\$licados al dise0o 2 o\$eraci0n de los sistemas de \$otencia hacia la con4ormaci0n de las redes inteli0entes e identi4ca las tendencias, barreras 2 \$osibles brechas en esta @ea. ' e describen modelos \$ara o\$timi3ar el dise0o 2 la o\$eraci0n de los sistemas de \$otencia considerando las ener09as renovables, la 0eneraci0n distribuida, las micro redes, la 0esti0n de la demanda 2 los sistemas de almacenamiento de ener09a. ' e conclu2= Aue es necesario validar muchos de los modelos Aue se han 4ormulado recientemente \$ara la o\$timi3aci0n de la o\$eraci0n mediante \$ruebas con datos reales 2 a 0ran escala. Adem@, la 0esti0n de la demanda 2 las micro redes son as\$ectos en los cuales se reAuieren desarrollar modelos \$ara el 4uib= \$timo de \$otencia. <inalmente, es necesario \$redecir con ma2or \$recisi0n las variables estoc@ticas \$ara Aue estos modelos se ada\$ten al com\$ortamiento real del sistema.

(alabras clave- o\$timi3aci0n; ener09as renovables; redes inteli0entes; 4uib= \$timo de \$otencia.

1. Introducci0n

Cos sistemas de \$otencia se encuentran en constante desarrollo, el \$ro0reso de las ciudades im\$ulsa el avance de los sistemas de suministro el@ctrico. ' on evidentes los 0randes cambios Aue se observan en los sistemas de \$otencia actuales con res\$ecto a d@cadas anteriores. >stos cambios a\$untan a aumentar la e4iciencia de los sistemas, disminuir el

im\$acto ambiental ocasionado \$or la 0eneraci0n de ener09a el@ctrica 2 0aranti3ar la sostenibilidad a lo lar0o del tiem\$o.

' e ha \$lanteado Aue una v9a \$ara el desarrollo sostenible de los sistemas de \$otencia es la con4ormaci0n de redes inteli0entes) art grids#. Cas redes inteli0entes son la inte0raci0n de la in4raestructura el@ctrica 2 de comunicaciones con tecnolo09as avanzadas de automati3aci0n e in4ormaci0n de \$procesos 194.

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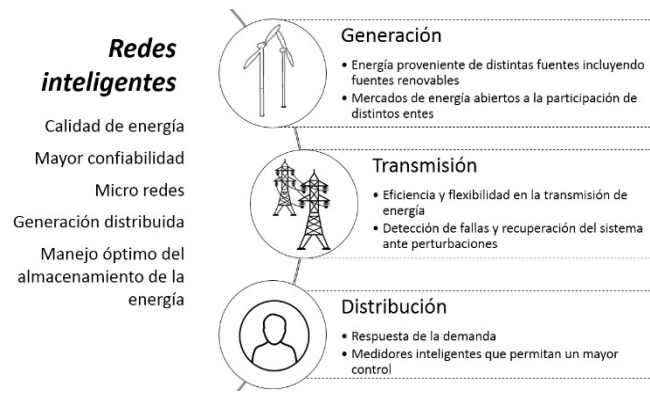


Figura 1. Características deseables de las redes inteligentes en general y su impacto en el sistema de potencia. Fuente: Elaborado por los autores.

El concepto de red inteligente es amplio, y su definición depende de las necesidades del sistema, este término se ha venido definiendo como una modernización del sistema de suministro de energía, para monitorizar, proteger y optimizar automáticamente la operación de los elementos interconectados [1]. De acuerdo con el Electric Power Research Institute (EPRI), algunos de los beneficios que se espera obtener de la implementación de redes inteligentes son: mayor confiabilidad y calidad de energía; seguridad y robustez ante eventos riesgosos; eficiencia energética; reducción de efectos ambientales; beneficios financieros [2].

En la Fig. 1 se muestra un resumen de las características deseables de las redes inteligentes, entre estas se buscan mayor eficiencia, mayor control y confiabilidad en el sistema de suministro eléctrico, tomando en cuenta las características de la red. Los requisitos de las redes inteligentes también aportan una mayor confiabilidad al sistema de suministro de energía, lo cual genera una serie de retos a ser atendidos [3]. Una manera de asegurar que la implementación de las redes inteligentes sea realmente ventajosa para el suministro eléctrico y su sostenibilidad, es aplicar técnicas de optimización para minimizar o maximizar ciertos factores deseados. Por ejemplo, en la planificación, la optimización permite aprovechar al máximo los recursos económicos y ambientales disponibles. Además, la optimización aplicada a la operación ayuda a garantizar condiciones de seguridad técnica durante el funcionamiento del sistema.

Las técnicas de optimización se han aplicado a los sistemas de potencia desde mediados de la década de 1940 [4]. En los últimos años han venido ocurriendo un gran número de avances en la planificación y en la operación de estos. Estas técnicas se han empleado para distintos tipos de problemas como: reducción del costo en el diseño de las instalaciones; minimización de costos en la operación de plantas de generación; minimización de emisiones en las plantas termoeléctricas; minimización de pérdidas en la operación; minimización de costos en el diseño de líneas de transmisión, entre otros.

Para resolver cada problema de optimización es necesario el planteamiento de un modelo que permita aplicar las técnicas matemáticas. Un modelo de optimización es una representación matemática de un sistema en la cual existe un conjunto de variables de decisión que deben

minimizarse o maximizarse para cumplir un objetivo, sujeta a unas restricciones. En la vista de la evolución de los sistemas de potencia, los modelos aplicados para la optimización deben integrar los cambios que se van realizando en la estructura de estos sistemas, de manera que se puedan aplicar a sus resultados sean representativos de la realidad.

En este sentido, en el presente trabajo inicialmente se describen algunos aspectos que se han considerado en las investigaciones más recientes relacionadas con las redes inteligentes y la nueva complejidad de los sistemas de potencia. Luego, se describen los modelos de optimización aplicados al diseño y la operación de los sistemas de potencia en el camino hacia la conformación de las redes inteligentes. Finalmente, se identifican las tendencias, las barreras y las posibles brechas que pueden existir en este ámbito de estudio.

2. Características y tendencias actuales de los sistemas de potencia

En la actualidad, para la reducción del impacto ambiental y la sostenibilidad a largo plazo del tiempo, se han implementado formas de generación basadas en fuentes renovables como la energía eólica, la energía solar y la energía hidráulica. La capacidad instalada a nivel mundial de estas fuentes de energía ha llegado a 2004 GW: la energía eólica, con un aumento del 8% con respecto al año 2000, incluyendo la generación hidroeléctrica [5].

En la transmisión de energía eléctrica, se ha buscado mayor eficiencia y confiabilidad, sobre todo en las largas distancias con el uso de líneas de transmisión en corriente directa (VLT), y la tecnología de transmisión directa (VLTDC). Este tipo de sistemas puede aportar ventajas como control del flujo de potencia, reducción de los costos y puede permitir la interconexión de sistemas asincrónicos [6].

En el ámbito de la distribución de energía, la generación distribuida y las micro redes son tendencias que se están implementando en la actualidad y que se visualizan como alternativas para reducir las pérdidas que existen en la transmisión de grandes bloques de energía a largas distancias. Entre las estrategias a nivel de distribución, la demanda activa o respuesta de la demanda, es otra manera que se está implementando para controlar el flujo de energía en los sistemas de potencia, se trata de que los consumidores puedan conocer su consumo eléctrico y tomar decisiones que ayuden a mejorar la operación del sistema. En el futuro, estas tecnologías se han aplicado principalmente en los países desarrollados y es un campo abierto de investigación para que sean de uso generalizado en el futuro.

2.1. Energías renovables

Uno de los avances más importantes en los sistemas de potencia ha sido el aprovechamiento de nuevas fuentes de energía, sobre todo aquellas que tienen un menor impacto ambiental. La generación de energía eléctrica mediante fuentes renovables está creciendo de forma acelerada, de hecho, durante el año 2000 a nivel mundial la capacidad instalada en: la energía renovable ha superado lo instalado en generación térmica, unos 40 GW: la energía renovable en comparación a 1990: la térmica [7]. De tal manera que la

tendencia mundial es hacia el crecimiento de las energías renovables. En años recientes esta situación ha sido evidente.

Dentro de las fuentes de energía renovables, la energía hídrica es la que tiene mayor capacidad instalada en el mundo, seguida por la energía eólica y la energía solar. En el mundo, en el 2010, la capacidad instalada en energía solar fotovoltaica estaba creciendo rápidamente, de igual manera la energía eólica presenta una tasa de crecimiento mayor a la hidroeléctrica. Como se muestra en la Fig. 2, el crecimiento de las fuentes de energía eólica y solar fotovoltaica ha sido sostenido en los últimos cinco años, estas tasas de crecimiento indican que en los próximos años se incrementará la penetración de las fuentes de energía renovables. De tal manera que se puede afirmar que los sistemas eléctricos en la actualidad y hacia el futuro están caracterizados por un incremento constante en la adición de nuevas fuentes de energía con un énfasis particular en las energías renovables.

2.2. Impacto de la variabilidad de la generación

La existencia de energías renovables como la energía solar y la energía eólica, implica que existe una dependencia de las condiciones climáticas para la generación de energía eléctrica. Como la naturaleza del clima es variable, si bien existen técnicas para predecir su comportamiento, siempre existen factores de incertidumbre. Como consecuencia

ambientales pueden afectar gravemente el funcionamiento de los sistemas de potencia, por ello se ha generado interés en el estudio de estos sistemas frente a cambios en las condiciones ambientales que pueden afectar la generación eléctrica.

Por su variabilidad, la alta penetración de energía eólica y energía solar puede afectar el diseño, el funcionamiento y la planificación de los sistemas de potencia. Se han realizado investigaciones para verificar el impacto de este tipo de generación en el sistema de potencia. Los resultados han mostrado que a medida que la generación eólica y solar aumenta, la demanda, se pueden presentar inconvenientes con el control de la frecuencia, estabilidad y el balance de potencia, de tal manera que para mantener la confiabilidad y la seguridad del sistema se hace necesario aumentar las reservas de potencia en el sistema eléctrico.

Löftholmen y cols. (2009) indican que la integración de grandes bloques de energía puede ayudar a mantener el balance de potencia y la confiabilidad del sistema mediante intercambios internacionales eléctricos. En el mundo, esto debe redundar en un fortalecimiento del sistema de transmisión para poder trasladar mayores bloques de energía y una mayor monitorización ante posibles eventos.

Por otro lado, la conexión de energía fotovoltaica a las redes trae efectos, tanto en estado estable como en estado transitorio. El impacto de la integración de energía fotovoltaica depende del nivel de penetración que puede tener en términos de la demanda total del sistema, así como también la topología de la conexión y el tipo de instalación; puede variar desde residencial hasta plantas fotovoltaicas a gran escala. En el mundo, a partir de niveles de penetración de un 10% con respecto a la generación total se observan desviaciones principalmente en el perfil de tensiones del sistema eléctrico.

2.3. Generación distribuida

Una de las tendencias en el suministro de la energía eléctrica es la generación distribuida, en general, se trata de proveer fuentes de potencia activa conectadas directamente a la red de distribución o en el punto de medición del usuario eléctrico. Este concepto también se conoce como generación descentralizada o embebida. Actualmente, se están implementando sistemas de generación distribuida mediante distintas tecnologías como generación térmica, energías renovables, celdas de combustible, entre otras. Como la mayoría de estas tecnologías necesitan de la electrónica de potencia para inyectar la potencia a la red de una manera eficiente y confiable, además de garantizar la calidad de la energía suministrada.

En comparación con los sistemas de potencia tradicionales centralizados, los sistemas basados en generación distribuida pueden reducir considerablemente las pérdidas en los alimentadores y las inversiones en redes de transmisión y distribución eléctrica. Estos sistemas permiten un soporte mutuo con la red macro, un mayor uso de los equipos y recursos disponibles y un suministro confiable con una mayor calidad, por lo tanto se puede aumentar la eficiencia y la seguridad de la red.

2.4. Sistemas de transmisión en corriente alterna flexibles

Los sistemas de transmisión flexibles en corriente alterna (FACTS). Flexible AC Transmission Systems son

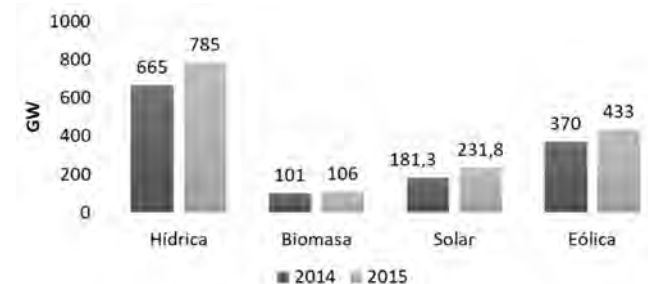


Figura 1. Capacidad instalada en las fuentes de energías renovables en los años 2014 y 2015.

Fuente: REN (2015).

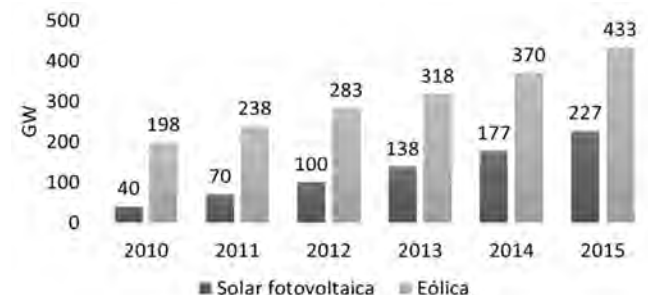


Figura 2. Crecimiento histórico de la capacidad instalada en las fuentes de energía solar fotovoltaica y energía eólica en los últimos cinco años.

Fuente: REN (2015).

dispositivos de electrónica de potencia que al ser instalados en una red de energía eléctrica permiten regular el flujo de potencia y mantener la estabilidad del sistema. Ellos proveen la impedancia deseada, potencia activa y potencia reactiva con el objetivo de mantener la estabilidad en todos los buses; incrementar los límites de carga y disminuir las pérdidas de potencia activa y reactiva del sistema de potencia.

Cos dispositivos <ACT> son usados actualmente debido a las prestaciones previamente mencionadas, se busca ampliar su aplicación para poder ejercer un mayor control sobre los intercambios de energía que ayudan a mantener el balance de potencia y la estabilidad en la red ante posibles variaciones de la generación o de la carga.

2. Transmisión en corriente directa

En los últimos años ha existido una tendencia hacia la transmisión en corriente directa, V-C, y voltaje direct current transmission debido a las ventajas que se han evidenciado sobre las líneas AC. Entre las ventajas está la reducción de las pérdidas debido a que en los sistemas LMDC no circula potencia reactiva; además, la capacidad de transmisión en LMDC es mayor debido a que no existe el efecto piel y el uso de menos conductores implica un menor costo y un menor peso, en grandes distancias. Adicionalmente, hoy en día la eficiencia y capacidad de control de los convertidores AC/DC y DC/AC han mejorado con respecto a los anteriores.

Gracias a las ventajas que se han mencionado, los sistemas LMDC están siendo empleados para la conexión de las plantas eléctricas costeras a tierra, dado que se reducen los inconvenientes de la transmisión AC por cable subacuático. También, se está empleando este tipo de líneas de transmisión para conexiones internacionales y entre redes de características diferentes en cuanto a frecuencia y niveles de tensión, puesto que los convertidores AC/DC con tecnología actual permiten controlar la frecuencia del sistema y adecuar el nivel de tensión para el intercambio de energía.

Inicialmente la tecnología LMDC estaba basada en tiristores, pero se ha desarrollado tecnología basada en transistores, lo cual permite obtener casi todas las mejoras de los controladores <ACT> individuales, esto es, transferencia de grandes bloques de potencia, entregar o absorber una cierta cantidad de potencia reactiva necesaria para mantener la tensión, controlar rápidamente emergencias para evitar niveles muy altos de corrientes de falla, entre otras.

2.1. Almacenamiento de energía

Un sistema de almacenamiento de energía tiene la capacidad de cargarse y descargarse de manera eficiente para acumular y ceder energía y suministrarlos cuando sea oportuno. Los desarrollos recientes en las tecnologías de la electrónica de potencia han hecho que la aplicación de las técnicas de almacenamiento de energía sea una solución viable para los sistemas de potencia modernos.

Entre las tecnologías que se emplean como sistemas de almacenamiento de energía se encuentran los sistemas de bombeo hidráulicos y de aire comprimido, las baterías, los

bancos de condensadores, los volantes de inercia, el almacenamiento superconductor de energía magnética y los sistemas de almacenamiento híbridos. Recientemente, los sistemas de almacenamiento híbridos han tomado auge y permiten integrar las bondades de distintas tecnologías en un mismo sistema.

En estos sistemas pueden aplicarse para solucionar distintos inconvenientes en los sistemas de potencia actuales. Por ejemplo, pueden ser empleados para balancear la red mediante servicios auxiliares, seguimiento y nivelación de carga. Además, pueden servir para el incremento de la reserva para manejar la incertidumbre de la generación eléctrica, lo cual puede ayudar a mejorar la eficiencia en la operación del sistema, mejorar la absorción de potencia, disminuir el costo del combustible y reducir las emisiones de CO₂ y SO₂.

2.2. Gestión de la demanda

En la evolución de los sistemas de potencia hacia redes inteligentes, se ha concluido que los consumidores tienen un papel muy importante y que pueden contribuir a mejorar el desempeño de la red. La gestión de la demanda consiste en emplear incentivos para lograr adecuar los patrones de consumo para mejorar el funcionamiento de la red de potencia.

Los beneficios de la gestión de la demanda son técnicos, económicos y ambientales. En el ámbito técnico se puede incrementar la seguridad y la confiabilidad de la red, ya que el tiempo de respuesta de la demanda es mucho menor que el de las grandes plantas de generación. En el ámbito económico se puede lograr la reducción de los costos de demanda, evitando inversiones adicionales y en el aspecto ambiental, se pueden reducir las emisiones de gases contaminantes al evitar los costos de demanda. Generalmente son cubiertos con generación térmica y eólica.

Las estrategias de respuesta de la demanda son estrategias que se pueden aplicar para lograr modificar el consumo del usuario final, bien sea por cambios en el precio de la energía o por incentivos para reducir el consumo. Las estrategias de respuesta de la demanda pueden ser participativa directa del usuario o mediante mercados de electricidad u organismos encargados de la respuesta de demanda. En todo caso, con el uso de las comunicaciones digitales y los medidores inteligentes de energía, la respuesta de la demanda se convierte en un mecanismo de control rápido en la red.

2.3. Micro redes

Una micro red es un sistema de potencia independiente que comprende generación distribuida, carga, almacenamiento de energía, dispositivos de control, en la cual la generación distribuida y el sistema de almacenamiento están directamente conectados al usuario en paralelo. Este tipo de sistema se ha venido estudiando desde comienzos de la década del 1990 y se plantea como un medio efectivo para convertir la red de distribución en una red activa, lo cual ayudará a la integración en gran escala de la generación distribuida y en la transición de la red de potencia tradicional a las redes de potencia inteligentes; la idea es convertir las redes de distribución de energía en sistemas que permitan la gestión más eficiente de la demanda.

2 la Oeneraci=n. Una de las ventajas de las micro redes es que pueden funcionar de forma aislada, lo cual permite suministrar energí a las zonas alejadas.

3. Modelos de optimización

La evolución de los sistemas de potencia implica una serie de ventajas. Entre las ventajas se encuentra una mayor flexibilidad, confiabilidad y control en el manejo de la energía. Por otra parte, esto implica una mayor complejidad del sistema y grandes inversiones en tecnología actualizada. Esto obliga a un campo abierto para los problemas de optimización, bien sea para la optimización de cada vez más complejos, para tomar decisiones en dilemas de costo-beneficio o para la optimización económica, confiable, sostenible y segura.

3.1. Optimización de sistemas con energías renovables y el impacto de la variabilidad de los recursos

Brevemente se han realizado varias revisiones sobre optimización aplicada a sistemas híbridos (E & F). Tomando en cuenta los modelos, métodos y herramientas que se han empleado, uno de los principales aspectos a los que se les ha aplicado

optimización es al diseño de sistemas híbridos. Los modelos de optimización del diseño de los sistemas híbridos se han concentrado en el dimensionamiento, combinaciones y localización de los componentes, tomando como principales restricciones los costos y la confiabilidad del sistema. Para poder evaluar los costos del diseño y su confiabilidad, se han empleado algunos índices que se muestran en la Tabla 1.

Cas fuentes de energía renovable con mayor crecimiento han sido foco de mayor número de investigaciones en optimización. De acuerdo con esto, el principal asunto de energía han sido los sistemas con generación eólica y fotovoltaica. Los aspectos de dimensionamiento y localización de estos tipos de energía han sido ampliamente abordados (E & F) desde la reducción de costos, emisiones y aumento de la confiabilidad.

Entre los recientes avances en los modelos de optimización para el diseño de sistemas con energías renovables, Rodríguez, Nauer y Nosman revisaron los modelos disponibles para el diseño de sistemas eólicos costeros y realizaron una propuesta de un modelo de optimización multiobjetivo para la localización de turbinas eólicas dentro de una cuadrícula rediseñada (E & F). AKN es necesario realizar distintas pruebas y comparaciones a este algoritmo.

Tabla 1

Índices para evaluar diseños de sistemas de potencia con energías renovables.

Índice	Descripción	Referencias
Índices para la evaluación de costos		
Costo Neto Presente (C. Net Present cost#)	Representa el costo de la energía de un sistema particular e incluye el costo inicial de todos los componentes del sistema, el costo de cualquier reembolso de componentes en el tiempo de vida del sistema y el costo del mantenimiento.	(E & F)
Costo total anualizado (C. Total annualized cost#)	Representa el costo por año del capital más el costo anual del mantenimiento y reparaciones de la instalación. Se puede calcular dividiendo el costo neto presente sobre el factor de anualidad de valor presente.	(E & F)
Costo del ciclo de vida (CC. Life cycle cost#)	Es la suma de todos los costos recurrentes y no recurrentes que tienen lugar durante el ciclo de vida de un sistema. Incluye precio de compra, instalación, costos operativos, mantenimiento y valor residual al final de su vida útil.	(E & H & F)
Costo de la energía (C. E/CE. Levelized cost of energy#)	Representa el costo de la energía como una relación entre el costo anualizado del sistema sobre la energía total generada.	(E, H & F)
Índices para la evaluación de la confiabilidad		
Probabilidad de pérdida del suministro (P. Loss of supply probability#)	Es la relación entre la pérdida de potencia suministrada sobre la demanda eléctrica en un cierto periodo de tiempo.	(E, H & F)
Probabilidad de pérdida de carga (Load loss probability#)	Se define como el periodo de falla sobre el tiempo de trabajo total del sistema.	(E & F)
Carga insatisfecha (Unserved load#)	Es la carga que no puede ser servida sobre el tiempo total de un periodo.	(E & H & F)
Nivel de desempeño del sistema (System performance level#)	Se define como la probabilidad de carga insatisfecha.	(E, H & F)
Horas de carga perdida (Lost load hours#)	Es la suma de la expectativa de pérdida en horas en un periodo determinado. Generalmente un año, se cuantifica el tiempo en el que el sistema no puede suministrar suficiente potencia para servir la carga evitando los efectos del mantenimiento y daños en componentes.	(E & F)
Riesgo de pérdida de carga (Loss of load risk#)	Se define como la probabilidad de que se genere una falla en el sistema para cubrir la demanda eléctrica diaria debido a deficiencias en las fuentes de energía renovable.	(E & F)
Nivel de autonomía (Level of autonomy#)	Trata con dos parámetros: el número total de horas en las que ocurre la pérdida de carga y el número total de horas de operación. Si la autonomía aumenta, el sistema será más confiable, pero a la vez el costo incrementa.	(E & F)
Otros índices		
Nivel de emisiones de carbono	Indica el nivel de emisiones de carbono desde un punto de vista esencial, se relaciona con la cantidad de energía generada o consumida a partir de fuentes térmicas.	(E & F)
Valor esperado (CVa*. Conditional value at risk#)	Es una medida del riesgo de la inversión, representa el valor esperado de los escenarios que se encuentran debajo de un cierto percentil de distribución.	(E & F)

Fuente: Elaborado por los autores.

>I en4Aue de modelar el dise?o de los sistemas h?bridos como un \$roblema de o\$timi3aci=n multiob?etivo tiene sentido a manera de lo0rar com\$romisos entre los distintos ndices Aue dan cuenta de la bondad de los sistemas. >ste en4Aue 2a se hab?a em\$leado \$ara el dise?o de sistemas h?bridos E*8,*HF 2 se ha im\$lementado en \$ro0ramas comerciales E 8F.

, tros \$roblemas de o\$timi3aci=n Aue se \$lantean tienen relaci=n con la o\$eraci=n del sistema. >stos se han es\$eci4cado con 4unciones ob?etivo Aue van desde la minimi3aci=n de costos hasta la reducci=n de \$Drddas, con restricciones sobre las variables de estado del sistema. Uno de los \$untos de inter?s en la o\$timi3aci=n de los sistemas con ener09as renovables como la solar o la e=lica es la variabilidad de dichos recursos. >n este sentido, se han reali3ado \$ro\$uestas \$ara el mane0 de la variabilidad introducida \$or las 4uentes de ener09a renovable.

7 artne3 2 Anderson \$ro\$usieron una 4ormulaci=n del com\$romiso de unidades con restricciones de se0uridad \$ara mane0ar alta \$eneraci=n de 0eneraci=n variable debida a 4uentes renovables. >I modelo se 4ormula como un \$roblema de o\$timi3aci=n \$robabil9stica c+ance9constrained o\$ti mization#, el cual \$ermite tomar en cuenta la incertidumbre en la 0eneraci=n 2 en la car0a E4" F. Gor su \$arte, Ta0havi 2 col. \$lantearon un des\$acho de \$otencia reactiva \$robabil9stico tomando en cuenta la variabilidad de las 4uentes de ener09a 2 otros elementos del sistema como <ACT" 2 L.MDC. >I modelo se 4ormul= como un \$roblema de o\$timi3aci=n con l=0ica di4usa lineal 2 se a\$lic= estimaci=n \$untal discreta \$ara la soluci=n. ' e demostr= Aue este modelo se \$uede em\$lear con menor car0a com\$utacional en com\$araci=n con otros m0dodos \$robabil9sticos como el m0dodo de 7 onte Carlo E49F. ' in embar0o, ambas \$ro\$uestas a4n necesitan ser \$robadas con sistemas a ma2or escala 2 datos reales.

' ummers 2 col. \$ro\$onen un modelo estoc@tico \$ara 4u00 = \$timo de \$otencia <, G# multi\$eriodo, Aue minimi3a los costos o\$erativos su0tos a varias restricciones. >n este trabajo se anali3aron dos nuevos en4Aues \$ara el <, G con variables estoc@ticas- a# el en4Aue d0dicit es\$erado 2 b# el en4Aue robusto en t0minos de la distribuci=n - istributionall&robust#, ambos \$aradi0mas de o\$timi3aci=n ba00 incertidumbre. 7 ediante et@m\$los num0ricos sim\$les se demostr= Aue estos en4Aues \$ermite tomar decisiones de com\$romiso entre costo 2 ries0o 2 Aue el se0undo otor0a una ma2or e\$ficiencia com\$utacional E* (E. No obstante, se recomienda estudiar m@ detalladamente los bene4icios de este ti\$so de o\$timi3aci=n 2 el desarrollo de al0oritmos de o\$timi3aci=n distribuida \$ara su a\$licaci=n a sistemas en 0ran escala.

Como se ha mencionado, uno de los @mbitos Aue no se ha cubierto en las investi0aciones relacionadas con o\$timi3aci=n de sistemas con ener09as renovables es la adecuaci=n 2 la a\$licaci=n de los modelos \$lanteados a redes en 0ran escala. ' e \$uede a4irmar Aue los modelos \$resentados se encuentran a4n en 4ase de \$ruebas 2 se hace necesario reali3ar \$ruebas con datos reales.

3.2. &odelos para el dise?o) operaci3n de la generaci3n distribuida) las micro redes

Actualmente e/ iste un creciente inter?s \$or el desarrollo 2 me0ramiento de los \$ro0ramas 2 al0oritmos \$ara la o\$timi3aci=n del dise?o de sistemas de 0eneraci=n distribuida. >stas t0nicas deben cubrir los \$rinci\$ales detalles de dise?o, evaluar el ries0o considerando la

incertidumbre 2 tener alta \$recisi=n en la b0ksAueda de la soluci=n.

>n relaci=n a la \$lani4caci=n de la 0eneraci=n distribuida, la locali3aci=n adecuada de las unidades Bue0a un \$a\$el crucial en el me0ramiento del desempe?o del sistema; \$or lo tanto la locali3aci=n = \$tima de la 0eneraci=n distribuida en los sistemas de \$otencia ha sido un \$unto de inter?s en las investi0aciones actuales. Adicionalmente, la 0eneraci=n distribuida de 4uentes renovables trae consi0o variabilidad e incertidumbre. >n este sentido, At5 a 2 >I&aadan2 \$ro\$usieron una t0cnica \$robabil9stica \$ara la locali3aci=n de 0eneraci=n e=lica distribuida 4ormulada como un \$roblema de o\$timi3aci=n lineal entera mi/ ta, el cual mostr= resultados m@ \$recisos Aue otros m0dodos basados en 4actores de ca\$acidad E4! F.

Abdela3i3 2 col. dise?aron un al0orismo \$ara modelar 0eneraci=n distribuida basada en 4uentes renovables \$ara la \$lani4caci=n de redes desbalanceadas. Co0raron inte0rar modelos \$robabil9sticos de la car0a, la 0eneraci=n e=lica 2 la 0eneraci=n 4otovoltaiica, 2 determinar la locali3aci=n = \$tima de la 0eneraci=n en el sistema de distribuci=n. Con esto, se obtuvo una reducci=n considerable de las \$Drddas anuales debidas a la inte0raci=n de la 0eneraci=n distribuida E4" F.

, tros trabajos como el de Gen0 2 col. tambi0n se han en4ocado en la locali3aci=n = \$tima de la 0eneraci=n distribuida mediante m0dodos estad9sticos. ' in embar0o, el modelo em\$leado en esta investi0aci=n se di4erencia \$or tomar en cuenta la minimi3aci=n de las emisiones contaminantes en confunto con los costos 2 las \$Drddas E4* F.

Gor otra \$arte, ' hah3ad 2 col. introdujeron el conce\$to de 4actor de concentraci=n de car0a 4CF. 4oad concentration factor# \$ara la o\$timi3aci=n de la locali3aci=n de la 0eneraci=n distribuida, el m0dodo \$ro\$uesto sim\$li4ca los c@culos necesarios \$ara minimi3ar las \$Drddas 2 adecuar el \$er41 de tensiones E44F. >I 4actor de concentraci=n de car0a indica la cantidad de car0a conectada en un cierto \$unto del sistema de \$otencia.

Theo 2 col. revisaron recientemente las t0nicas de \$lani4caci=n 2 o\$timi3aci=n \$ara 0eneraci=n distribuida 2 resaltaron los \$rinci\$ales a\$ectos a me0rar en este @mbito E4+ F. >nre ellos-

% >valuaci=n de los recursos renovables- em\$lear t0nicas modernas \$ara \$redicci=n de los datos meteorol=0icos \$uede me0rar la con4abilidad de los dise?os.

!. 7 odelos de la 0eneraci=n- actualmente son mu2 es\$ec94icos, \$or lo Aue se necesita 0eneralizarlos 2 desarrollar modelos \$ara nuevas tecnolog09as.

*, 7 odelo de la car0a- \$articularmente en el @mbito industrial se recomienda inda0ar sobre los im\$factos de distintos ti\$os de \$procesos en la demanda el0ctrica.

4. 7 odelo del almacenamiento de ener09a- se reAuiere desarrollar modelos detallados de los sistemas de almacenamiento de acuerdo a la tecnolog09a actual.

Gor otro lado, e/ iste la necesidad de me0rar el des\$acho de la 0eneraci=n distribuida de manera Aue la o\$eraci=n del sistema sea lo m@ e\$iciente \$osible. >n este @mbito, se han desarrollado modelos de des\$acho de 0eneraci=n distribuida Aue toman en consideraci=n criterios t0nicos 2 econ=omicos \$ara o\$timi3ar la o\$eraci=n de la red, entre ellos el desarrollado \$or Ansarian 2 col. E41F, el cual se basa en una

función multiobjetivo de usar la optimización de forma simultánea costos, confiabilidad, pérdidas y seral de tensiones.

La generación distribuida y las micro redes se encuentran ampliamente relacionadas. Se puede decir que las micro redes son una evolución natural de la generación distribuida. De hecho, el primer concepto introducido por Casseter y col. las define como una solución para aprovechar la potencialidad de la generación distribuida integrándolas a las carcas, donde el conjunto de carcas y microgeneradores opera como un sistema suministrando potencia y calor [4]. De acuerdo con la revisión realizada por Athima y Galanis [2] las inversiones con respecto a la optimización de sistemas de generación híbridos y micro redes han aumentado principalmente los aspectos económicos y ambientales, aunque también son importantes las restricciones que garantizan la calidad de la energía y la estabilidad del sistema para la interconexión con la red eléctrica.

> El diseño de micro redes aisladas se ha formulado como el problema de optimización, el cual permite obtener los tamaños apropiados de los componentes minimizando los costos y restringiendo la CG y la EF. Recientemente, se han realizado distintas formulaciones para el problema del dimensionamiento de las micro redes tomando en cuenta la generación híbrida y el almacenamiento de energía [4, 18]. De acuerdo con: Amarra y col. [9] el análisis de sensibilidad se ha revelado como un caso crítico en la planificación de micro redes para desarrollar un diseño robusto en términos de confiabilidad económica.

> En términos del control de la operación del sistema, uno de los problemas más importantes es decidir el modo de operación de la micro red, es decir, operar conectada a la red principal u operar en modo isla. > En el caso de micro redes aisladas, se han realizado formulaciones de despacho de potencia activa y reactiva, y el tiempo de potencia considerando la interacción entre fuentes de energía convencionales y fuentes renovables [9, 18].

Otra parte, se ha considerado la operación de micro redes conectadas a sistema de potencia macro. > En este sentido, se ha modelado la red de potencia como un sistema de sistemas mediante una estrategia de control que incorpora recursos de energía distribuidos, dispositivos de almacenamiento y carcas; se emplea una función objetivo para minimizar los intercambios de potencia entre las micro redes y garantizar el funcionamiento dentro de límites técnicos [9]. En embargo, este enfoque es preliminar y aun es necesario formular un modelo detallado de el tiempo de potencia para la red con micro redes en funcionamiento.

3.3. Interacción de los sistemas de transmisión

Como se ha mencionado, la evolución de los sistemas de potencia hacia redes inteligentes implica una mayor confiabilidad y control en la transmisión de energía eléctrica; los $FACTS$ y la transmisión en LMDC permiten sortar estas características a los sistemas de potencia.

Una de las características en común de los $FACTS$ y las

líneas de transmisión en LMDC es que dependen de dispositivos de electrónica de potencia, por lo tanto, uno de los puntos de interés ha sido integrar estos dispositivos a modelos de optimización de la operación, como el despacho de potencia o el tiempo de potencia. > En tal sentido, se han formulado varias investigaciones [8, 19].

Recientemente, Manitha y col. [9] usaron un método que considera varias funciones objetivo para el problema de el tiempo de potencia incorporando dispositivos $FACTS$ como lo son los compensadores estáticos sincrónicos (TATC, STATCOM, SSSC, etc.). Demostraron la aplicación del algoritmo de evolución diferencial y la programación adaptativa de uso con fines para la evaluación de múltiples objetivos, como una solución estocástica al sistema [9].

Muchos autores han tratado de integrar la transmisión en LMDC en la formulación del problema de el tiempo de potencia mediante distintos modelos [4, 18, 19]. Principalmente se han utilizado modelos basados en métodos heurísticos y en inteligencia artificial para lidiar con la complejidad matemática de los modelos de dispositivos de electrónica de potencia.

Una de las aplicaciones de la transmisión LMDC es la conexión de plantas eólicas costeras. Rahrh y Amin [9] usaron un modelo de planificación de grandes plantas eólicas costeras conectadas mediante un sistema de transmisión en LMDC con múltiples terminales. En embargo, esta propuesta necesita ser implementada en casos reales para su validación completa [9].

Otra parte, se ha buscado optimizar la localización y el número de los dispositivos $FACTS$ en la red de transmisión, para lo cual se han formulado distintos modelos para optimizar la localización de los $FACTS$ [18].

3.4. Gestión de la demanda óptima

Mardas y col. [19] revisaron los programas de respuesta de la demanda, los métodos de tarificación y algoritmos de optimización. > Esta investigación obtuvo algunas conclusiones importantes para la optimización de la demanda:

- Los esquemas de respuesta de la demanda tienden a tener un mayor éxito mientras la participación de los usuarios finales es mayor, por lo tanto estos esquemas deben ser atractivos y apropiados al tipo de usuario.

- Para optimizar la gestión de la demanda es esencial la predicción precisa de la demanda en tiempo real, para lo cual se han aplicado algoritmos basados en lógica difusa, teoría de redes neuronales, pero es un campo que todavía tiene mucho por explorar.

- Otro pilar fundamental para lograr la gestión de la demanda es la disponibilidad de datos precisos del sistema en tiempo real, es por ello que las tecnologías para la monitorización del sistema serán decisivas en la evolución hacia las redes inteligentes.

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- E%F Manitha, R., Na\$aran, 6. and ' udha; aran, 7 ., 7 ulti , b\$ective , \$timal Go5 er <o5 5ith ' TATC, 7 usin0 D> in I A<: G,)ndian 6. ' ci. Technol., 81, \$\$. %4444B, ! "% D,)-%.%48+!Bt. ! "%v81%+11+4
- E%F Rim, C.R., ' ood, M.R., 6an0, : ' ., C'm, ' .6. and Cee, ' .6, LMDC Transmission- Go5 er Conversion A\$\$\$ications in Go5 er ' 2stems. I ile2, ! "%H
- E%F Carri3osa, 7 .6.6., Navas, <.D., Damm, : . and Camnabhi&Caarri0ue, <<., , \$timal \$o5 er 4o5 in multi&terminal LMDC 0rids 5ith o4shore 5 ind 4arms and stora0e devices,)nt. 6. >lectr. Go5 er >ner02 ' 2st., 1+, \$\$. !H44B, ! "% D,)-%.%%4.Bt\$es. ! "%4.%."4
- E" F Rondoh, 6. et al., >lectrical ener02 stora0e s2stems 4or ener02 net5 or; s, >ner02 Convers. 7 an0., 4%# \$\$. %81*88(4, ! "%.
- E" F Cuo, U., I an0, 6., Dooner, 7 . and Clar; e, 6., , vervie5 o4current development in electrical ener02 stora0e technologies and the a\$\$\$lication \$otential in \$o5 er s2stem o\$eration, A\$\$. >ner02, %8(, \$\$. +%%4*1, ! "% D,)-%.%%4.Ba\$ener02. ! "%4."H"8%
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- E1F ' iano, G., Demand re\$on\$e and smart 0rids &A surve2, rene5. ' u\$tain. >ner02 Rev., **, \$\$. 41%44(8, ! "%.
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- EHF Nhandari, N., Cee, R.8T., Cee, : .8T., Cho, Y.8T. and Ahn, ' .8T., , \$timi3ation o4 h2brid rene5 able ener02 s2stems- A revie5,)nt. 6. Grecis. >n0. 7 anu4 Technol., ! %4 \$\$. H888, ! "%.
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- E%F Camar0o, C.A.' ., Ramos, D.' ., : uarnier, >.,)shida, ' . and 7 atsudo, >., Alternative 0eneration sources \$ort4olio- , \$timal resource allocation and ris; anal2sis su\$orted b2 0enetics al0orithms,)>>> Cat. Am. Trans., %4 (\$\$. *1*! &4% ! "%.
- E! F Abdela3i3, A.Y., Le0a32, Y.: ., >1&hattam, I . and , thman, 7 .7 ., , \$timal allocation o4 stochasticall2 de\$endent rene5 able ener02 based distributed 0erators in unbalanced distribution net5 or; s, >lectr. Go5 er ' 2st. Res., %41 \$\$. *444, ! "% D,)-%.%%4.Brser. ! "%4."H"+
- E* F I an0, 6. and Yan0, <., , \$timal ca\$acit2 allocation o4 standalone 5 ind.solar.batter2 h2brid \$o5 er s2stem based on im\$roved \$article s5 arm o\$timisation al0orithm, >T Rene5. Go5 er : ener., (+# \$\$. 44*848, ! "%.
- E4F Thou, I ., Cou, C., Ci, T., Cu, C. and Yan0, L., Current status o4 research on o\$timum \$i3in0 o4 standalone h2brid solar& ind \$o5 er 0eneration s2stems, A\$\$. >ner02, 8(!# \$\$. *8' &8H ! "%.
- E+ F Rodri0ues, ' ., Nauer, G. and Nosman, G.A.N., 7 ulti&b\$ective o\$timizati0n o45 ind 4arm la2outs &Com\$le/ it2, constraint handlin0 and scalability, Rene5. ' u\$tain. >ner02 Rev., 1+, \$\$. +8(&"H ! "%.
- E1F Yan0, 6., <en0, U., Tan0, Y., Yan, 6., Le, L. and Cuo, C., A \$o5 er s2stem o\$timal di\$atch strate02 considerin0 the 4o5 o4 carbon emissions and lar0e consumers, >ner0ies, 8 H# \$\$. H'8(&41, ! "% D,)-%.**H'.en8'H'8(
- E(F ' ummers, T., I arrin0ton, 6., 7 orari, 7 . and C20eros, 6., ' tochastic o\$timal \$o5 er 4o5 based on conditional value at ris; and distributional robustness,)nt. 6. >lectr. Go5 er >ner02 ' 2st., (!, \$\$. %8444+, ! "% D,)-%.%%4.Bt\$es. ! "%4."!4
- E8F Du4o&=Se3, R. and Nernal&A0ust9, 6.C., 7 ulti&b\$ective desi0n o4 GM& ind&iesel&2dro0en&batter2 s2stems, Rene5. >ner02, ** %4 \$\$. !++H4(+, ! "%8.
- E" F ' , uld&Nilal, N., ' ambou, M., Ndia2e, G.A., RDbD C.7 .<. and Ndon0o, 7 ., , \$timal desi0n o4 a h2brid solar& ind&batter2 s2stem usin0 the minimizati0n o4 the annuali3ed cost s2stem and the minimizati0n o4 the loss o4\$o5 er su\$512 \$robabilit2 CG G# Rene5. >ner02, +* %4 \$\$. !*88&*H', D,)-%.%%4.Brene. ! "%4."*""4
- E4 F 7 artine3, : ., Anderson, C.C., Anderson, C. and 7 artne3, : ., To5 and a scalable chance&constrained 4ormulation 4or unit commitment to mana0e hi0h \$eneration o4 variable 0eneration, en +!nd Annual Allerton Conference on Communication, Control, and Com\$utin0, Allerton ! "%4, \$\$. (!&*", ! "%.
- E4 F Ta0havi, R., Re3a, A. and ' amet, L., ' tochastic reactive \$o5 er di\$atch in h2brid \$o5 er s2stem 5ith intermittent 5 ind \$o5 er 0eneration, 8H ! "%.
- E! F At5 a, Y.7 . and >1&aadan2, >., , Grobabilistic a\$roach 4or o\$timal allocate on o4 5 ind&based distributed 0eneration in distribution s2stems, >T Rene5. Go5 er : ener., + %4 \$\$. (H88, ! "% D,)-%.%4Hiet&0. ! "%H""%
- E4 F Gen0, U., C'm, C., Then0, I . and Ciu, Y., Crisscross o\$timizati0n al0orithm and monte carlo simulation 4or solvin0 o\$timal distributed 0eneration allocation \$problem, >ner0ies, 8 %4 \$\$. %814&41+H ! "%.
- E4F ' hah3ad, 7 ., Ahmad,), : a5 li; , I . and Galen3, 2, G., Coad concentration 4actor based anal2tical method 4or o\$timal \$lacement o4 multi\$le distribution 0erators 4or loss minimizati0n and volta0e \$ro4le im\$rovement, >ner0ies, H4# ! "%.
- E4 F Theo, I .C., C'm, 6' ., Lo, I ., Lashim, L. and Cee, C.T., Revie5 o4 distributed 0eneration D: # s2stem \$lannin0 and o\$timisation techniAues- Com\$arison o4 numerical and mathematical modellin0 methods, Rene5. ' u\$tain. >ner02 Rev., 1(, \$\$. +%4*(*, ! "% D,)-%.%%4.Brser. ! "%4."H"1*
- E4 F Ansarian, 7 ., ' ade0h3adeh, ' .7 . and <otuhi&ru3abad, 7 ., , \$timum 0eneration di\$atchin0 o4 distributed resources in smart 0rids, ! "%.
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- E8F Nhui2an, <.A., Ya3dani, A. and Grima; , ' .C., , \$timal \$i3in0 a\$roach 4or islanded micro0rids, >T Rene5. Go5 er : ener., H !# \$\$. %4184+, ! "%.
- E4F 7 a, Y., 6, 6. and Tan0, U., Tri\$le&b\$ective o\$timal \$i3in0 based on d2namic strate02 4or an islanded h2brid ener02 micro0rid,)nt. 6. : reen >ner02, November, ! "%.
- E" F <ossati, 6.G.; alar3a, A., 7 artne3&Millate, A. and <ont@, C., A method 4or o\$timal \$i3in0 ener02 stora0e s2stems 4or micro0rids, Rene5. >ner02, ((, \$\$. +*H44H ! "%.
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- B4F Thao, N., Than0, U., Chen, 6, I an0, C. and : uo, C., , \$eration o\$timization o4 standalone micro0rids considerin0 li4etime characteristics o4 batter2 ener02 storage s2stem, > > > Trans. 'ustain. >ner02, 4 4#, \$\$. H*484, !"% . D,)-%.%%HT' T>.! "%!!484"
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- B8F Ganda, A. and Tri\$ath2, 7 ., ' ecurit2 constrained o\$timal \$o5 er 4o5 solution o4 5 ind \$thermal 0eneration s2stem usin0 modi4ed bacteria 4ora0in0 al0orithm, >ner02, H*, \$\$. 8%88(, !"% . D,)-%.%%d.Bener02.! "%%."H"8*
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- El!F Rhrailh, 7 ., 7 ember, ' ., Arabia, ' ., 7 ember, C. and Arabia, ' ., , \$timitation \$lannin0 4or lar0e & scale o4 shore 5 ind 4arms usin0 multi & terminal LMDC transmission s2stem, smart 0rid, \$\$. %4, !"%.
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- El+F Ravi, R. and Ral0ram, 7 ., , \$timal location o4 <ACT' devices usin0 Jm\$roved Carticle' 5 arm , \$timitation, Jnt. 6. >lectr. Go5 er >ner02 ' 2st., 4H%#, \$\$. ***8*8, !"%.
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- El+F Ganda, A. and Tri\$ath2, 7 ., ' ecurit2 constrained o\$timal \$o5 er 4o5 solution o4 5 ind \$thermal 0eneration s2stem usin0 modi4ed bacteria 4ora0in0 al0orithm, >ner02, H*, \$\$. 8%88(, !"% . D,)-%.%%d.Bener02.! "%%."H"8*
- El1F 'aunders, C.' ., Goint estimate method addressin0 correlated 5 ind \$o5 er 4or \$robabilistic o\$timal \$o5 er 4o5 , > > > Trans. Go5 er ' 2st., !H%#, \$\$. %4+88+4, !"%.
- El(F Raur, 7 ., Ne5 ton\$ method as\$roach 4or securit2 constrained , < usin0 TC' C, en %8 > > > Jnternational Conference on Go5 er >lectronics, Jntellioent Control and >ner02 ' 2stems, !"% . D,)-%.%%H)CG>C>' !"%.(8+*4*(

, . &ello-Maita, se titul= como Jn0. >lectricista en la Universidad del Tulia, Mene3uela en !""H con distincin= n' umma Cum Caude. >n el a2o !""% in0resa como Necaria Acadmica en esta instituci=n 2 en ella obtiene el t\$ulo de 7 'c. 'cientiarum en 7 atem@ica A\$licada. A \$artir de !""% se desem\$ea como docente e investi0adora. 'u \$rinci\$al l9hea de investi0aci=n es o\$timizaci=n de sistemas de \$otencia, tambi0n \$artici\$a en \$ro2ectos de investi0aci=n sobre ener0as alternativas 2 e4ciencia ener0ica. Actualmente cursa el \$ro0rama de doctorado en Jn0enier\$a en la Universidad del Tulia, Mene3uela , RC)D- """"&""%88H+8H4U

A. Marulanda- uerra. obtuvo su 0rado de Jn0. >lectricista en %H4, \$or la Universidad del Tulia, Mene3uela. Dr. en Jn0enier\$a >Idtrica \$or la Universidad de 'evilla, >\$sa?a !""4# ' e ha desem\$e?ado como \$ro4esor e investi0ador en sistema de \$otencia en la >scuela de Jn0enier\$a >Idtrica de la Universidad del Tulia 2 actualmente es miembro del : ru\$0 de investi0aci=n 7 odelado >stratDico en >ner0a 2 Cotencia de la >scuela Colombiana de Jn0enier\$a Gulio : aravito. ' us \$rinci\$ales @eas de interDs son- o\$timizaci=n de sistemas de \$otencia, ener0as alternativas, redes inteli0entes 2 micro redes , RC)D- """"&""%8((*H814%

Convective drying of Cucurbita moschata# influence of temperature and air velocity on effective moisture diffusivity, carotenoid content and total phenols

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Abstract

The influence of air temperature and air velocity on convection drying of Cucurbita moschata "UNAPA# Abanico" is studied using kinetics and changes in the content of total phenolic and carotene compounds. The response surface methodology as used to optimize the drying conditions for Cucurbita moschata. The studied factors included drying temperature (4, 6, 8 and 10 °C) and air velocity (0.5, 1.0, 1.5 and 2.0 m/s). The optimum drying conditions were 6 °C and 1.0 m/s for the air temperature and velocity, respectively. The drying time was 2.4 h. The four had 2.4 A °C, B °C, C °C and D °C for moisture, %, A °C, B °C, C °C and D °C for total carotenoids and % A °C, B °C, C °C and D °C for total phenols.

Keywords: Convective drying; Cucurbita moschata "UNAPA# Abanico"; total phenols; carotenoids; response surface methodology; air temperature.

(Secado convectivo de Cucurbita moschata# influencia de la temperatura y velocidad de aire sobre la difusividad efectiva de humedad, contenido de carotenoides y fenoles totales)

Resumen

(Se estudió la influencia de la temperatura y la velocidad del aire en el secado convectivo de Cucurbita moschata "UNAPA# Abanico" por medio de la cinética de secado y los cambios en el contenido de compuestos fenólicos y carotenos totales. (Se empleó el método de superficie de respuesta para optimizar las condiciones de secado en el secado de Cucurbita moschata. Los factores estudiados fueron, temperatura de secado (4, 6, 8 y 10 °C) y velocidad de aire (0.5, 1.0, 1.5 y 2.0 m/s). Las condiciones óptimas de secado de Cucurbita moschata fueron 6 °C y 1.0 m/s, respectivamente. El tiempo de secado fue de 2.4 h. Los cuatro grupos de muestra tuvieron 2.4 A °C, B °C, C °C y D °C de humedad, %, A °C, B °C, C °C y D °C de carotenoides totales; y A °C, B °C, C °C y D °C de fenoles totales; y A °C, B °C, C °C y D °C de muestra.

Palabras clave) (Secado convectivo; Cucurbita moschata "UNAPA# Abanico"; fenoles totales; carotenoides; metodología de superficie de respuesta; temperatura del aire.

1. Introduction

The Cucurbita moschata variety Una# Abanico, is the result of different genetic crosses between selections of Cucurbita moschata made by the Universidad Nacional de Colombia, Palmira. Its fruit is characterized by a high content of dry

matter but low water content. This horticultural crop has a high potential for agriculture because of its nutritional value and is used for fresh consumption and processed foods, such as flour, sugar and dehydrated products. J%K (important contents of the flour) have been identified in Cucurbita moschata: ascorbic acid, vitamin C, minerals, calcium, iron,

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Shenolic compounds: amino acids, thiamine and niacin, phenolic compounds, +2 A %8 & %88% A 4 m1 CAD/%"1 o4 dr3 sam\$le# and \$ro&vitamin A in the 4orm o4 total carotenoids 4 " .%&8%2, .8 L1/1#J! ,+4K

This crop is perishable because of its high moisture content. "B# causes it to deteriorate? it in a 4e? ? ees o4 harvest J, K 6reservin \$um\$>in ? ith its nutritional, functional, flavor and color characteristics is a difficult task. J2,) K dr3in1 ? ith hot air is one o4 the more 4re5uent techni5ues used to achieve this. Currentl3, this techni5ue is used in \$ost&harvest \$rocesse5 o4 a1rcultural \$roducts and 1rains, eliminatin1 \$art o4 the ? ater throu1h \$rocesse5 o4 tran5fer o4 mass and heat, simultaneousl3. This decrease in moisture minimizes the \$henomenon o4 deterioration b3 microor1anisms or en<3mes in 4oods J8,' K ; o? ever, dr3in1 ? ith hot air leads to a loss o4 \$roduct 5ualit3 in terms o4 taste, color, and nutritional and functional contents in terms o4 bioactive compounds such as \$henols and total carotenoids J%K

Different studies have been \$resented on >inetics o4 hot air \$um\$>in dr3in1, either ? ith the ob1ective o4 determinin1 mass tran5fer, ener13 re5uired to deh3drate or sam\$le la3er thic>ness J) ,%K ; o? ever, other dr3in1 techni5ues have also been studied; - smotic deh3dration - D#, micro? ave, hot air and combined micro? ave, vacuum dr3in1, amon1 others J2,%&4K (imilarl3, more complete studies are made on slices o4 \$um\$>in, ? hich have the in4uence o4 dr3in1 in terms o4 color, sensor3 evaluation, total carotenoid content, \$henolic acids more abundant and beta&carotene delradation J4,! ,%K ; o? ever, the e4fect o4 dr3in1 ? ith hot air on carotenoids and \$henols ? as not addressed ? ith the UNA6AE Abanico), \$um\$>in variet3, ? hich is characteri<ed b3 a \$romisin1 vegetable 4or a1roindustrial \$ur5oses, due to its high content o4 dr3 matter J%K

Therefore, this ? or> aims to investigate the in4uence o4 the variables tem\$erature and air velocit3# in the dr3in1 \$rocess on the characteristics o4 the 4nal \$roduct, aimin1 to investigate the e4fect o4 air tem\$erature and dr3in1 rate on the 4resh 5uash \$ul\$ in terms o4 4nal moisture content N9 C#, carotenoids TC# and total \$henolic content T6C#.

2. Materials and method

6um\$>in 4ruits UNA6AE&Abanico), variet3# ? ere collected 4rom the municipalities o4 Da1ua and Yumbo 8 alle de Cauca & Colombia#, 4., months old. The 4ruits ? ere ? ashed, cut, and blanched at a boilin1 tem\$erature 4or ' minutes. The \$ul\$? as se\$arated and cut ".+0)0"., cm# in a 4ood \$rocessor =avar, Colombia#.

2.1. Determination of moisture and quantification of total phenols and carotenoids

!.%% Determination o4 moisture content N9 C#

The moisture \$ercentage B9 #? as determined ? ith the 4nal and initial ? ei1hts usin1 a moisture balance O9 2" eP". "%6recision, (? iss#; see D5. %K.

$$\% \text{Moisture} = \frac{\text{Final weight}}{\text{Initial weight}} * 100 \quad (1)$$

!.%! . Quantification o4 total carotenoids TC#

The carotenoids ? ere 5uantified in tri\$licate J%, %2K". "% A". "%%1 o4 the sam\$le bh#? as ta>en and ? ei1hed in a test tube; seven)# mE o4 a 4.+ ethanol&he0ane solution ? ere added, \$rotected 4rom li1ht in a cold bath ! @# and stirred 4or 2" min on an orbital sha>er 9 RC T- (&4"+N, U(A#at !, " r\$m. (ubse5uentl3, %mE o4 distilled ? ater ? as added and stirred 4or % min. The absorbance o4 the sam\$les at 4, " nm ? as read against a he0ane blan> '). "B (i1ma&Aldrich, (\$ain#. A (\$ectro\$hotometer U8 & is, =en? a3 2+!"D, ? as used. The total carotenoid content o4 the he0ane e0tracts ? as calculated ? ith D5. !#.

$$\frac{TC (mg)}{100 (g)db} = \frac{A450 \times 536.85 \times 3}{0,001 \times 137.4} \quad (2)$$

R here , +2.8, 1/mol is the molecular ? ei1ht o4 S&carotene, + is the volume mE# o4 he0ane, ". "%1 is the ? ei1ht o4 the added sam\$le, and %> .4 m.9 % is the e0tinction coefficient 4or S&carotene in he0ane.

!.%+. Determination o4 the total \$henolic content T6C#

6um\$>in 4our ? as e0tracted ? ith % mE o4 8"B methanol CC#(i1ma&Aldrich Cerman3#. The sam\$les ? ere centri4u1ed at +"""" r\$m 4or % min at , @. The su\$ernatant ? as removed and \$assed throu1h a R alman 4ilter No. 4! . The T6C ? as determined accordin1 to J%K - ne milliliter o4 e0tract ? as \$laced in a !, ml container; nine milliliters o4 distilled ? ater and one milliliter o4 Nolin&Cicalteu reagent ? ere added, stirred and le4 to stand 4or , min; then, % mE o4), B NaC- + ? as added and brou1ht to !, ml ? ith distilled ? ater; the reaction ? as stirred and allo? ed to stand 4or 2" min at 4" @ in dar>ness. The absorbance at)2" nm ? as recorded usin1 a \$ectro\$hotometer U8 & *, (himad-u, model U8 &)"" 6harmasec#. A calibration curve o4 lallic acid +4., &rih3dro03ben<oic acid, (i1ma Chemical Co., (t. Eouis, 9 - , U(A# ? as obtained in an 8"B methanol solution ; 6EC 1rade methanol#, relatin1 the absorbance AT(# and concentration AT(P 4.))8) 0 concentration & ". """"+, R' P ". ' ' #. The results are e0\$ressed as lallic acid e5uivalents CAD# in ml/%" 1 o4 ra? material db#.

2.2. Drying process and data collection

The \$um\$>in \$ul\$ sam\$les ? ere deh3drated in a tra3 dr3er N°Q, Colombia#. The dr3in1 air velocit3 8 A(#? as regulated ? ith a velocit3 controller on the a0ial 4o? ventilation unit. The air ? as heated ? ith an electric device ? ith 4ve %""& resistors arran1ed in a unit se\$arate 4rom the dr3in1 chamber. The air tem\$erature TA(#? as controlled ? ith a heater \$o? er control unit. The \$um\$>in sam\$le, ? ith rectan1ular 1eometr3, ? as e0tended in the tra3 ? ith a load densit3 o4 %++ >1.m%. 6reliminar3 e0\$eriments ? ith anal3sis o4 variance selected the 4actors that a4fected the res\$onse variables and their ran1es. D0\$eriments ? ere carried out at the 4ollo? in1 intervals TA(4, @ to 2, @# 8 A(2 to 8 m.s%# in the transverse direction and \$rocesstime ++" to 2+" min# 9 easurements o4 tem\$erature, air

velocit3, and relative humidit3 o4the dr3in1 air ? ere recorded in the air inlet and outlet holes ever3 % min. The dr3 and ? et bulb tem\$eratures ? ere recorded ? ith thermocou\$les intelrated into the dr3in1 cabinet. A di1ital balance ? as used to record the ? ei1ht chan1eo4thesam\$leover time. Therelativehumidit3 and tem\$erature ? ere also measured ? ith a di1ital thermo h3trometer D0tech, 8 R R +, , %, U(A#

2.3. Diffusivity coefficient

The e4fective di4usivit3 ? as determined ? ith the second la? o4 Nic> D5. + # J), %8K The leometr3 o4 the \$um\$>in sam\$les ? as rectan1ular and neili1ible e0ternal contraction and resistance and uni4orm initial moisture distribution ? ere assumed. D5. 4#re\$resents the solution o4Nic>1a? and ? as used to determine the di4usivit3 constant o4each e0\$eriment.

$$\frac{\partial X}{\partial t} = -De_{ff} \frac{\partial^2 X}{\partial x^2} \quad (3)$$

R here X re\$resents the 1lobal moisture content B #, x is the len1th m# and t is time s#

$$MR = \frac{8}{\pi^2} e^{-\frac{\pi^2 De_{ff} t}{4L^2}} \quad (4)$$

MR re\$resents the moisture ratio, De_{ff} , is the e4fective di4usivit3 o4the moisture m¹ s⁴#, t is the dr3in1 time s# and E is hal4the thic>ness o4the \$um\$>in cut into rectan1les m#. Thecoe4cient o4di4usivit3 ? as calculated 4rom the lineari<ed slo\$ein D5. 4# The9 R value ? as calculated usin1 D5. , #

$$MR = \frac{X_t - X_e}{X_i - X_e} \quad (5)$$

? here X_i is the initial moisture content dr3 basis, X_t is the moisture content dr3 basis# at time t based on the recorded ? ei1ht, and X_e is the e5uilbrium moisture content.

2.4. Activation energy (Ea)

The activation ener13 ? as determined 4rom the e4fective di4usivit3 coe4cient at a constant air velocit3 2,) and 8 m.s⁴# at the di4ferent tem\$eratures associated ? ith the e0\$eriments. D5. 2# o4 Arrhenius ? as used 4or the determination.

$$De_f = De_{ff0} \exp \left(-\frac{E_a}{RT} \right) \quad (6)$$

R here E_a is the activation ener13 V=mol#, R is the universal constant o4the 1asses 8.+%4+ 0 %>=>mol V#, T is the air tem\$erature V#, and De_{ff0} is the di4usivit3 in m¹.s⁴#. The lineari<ed slo\$e based on D5. 2# is associated ? ith the activation ener13.

2. . E/ periment design

The res\$onse sur4ace methodolo13 ? as used to investi1ate the e4fects o4 TA(0# and 8 A(m.s⁴# on the

4nal moisture content N9 C#, TC and T6C durin1 the dr3in1 o4 the \$um\$>in \$ul\$. The ran1es o4 the \$rocess variables ? ere determined ? ith a \$reliminar3 e0\$eriment.

A central com\$osite rotar3 desi1n CCRD# ? as used, includin1 % e0\$eriments consistin1 o4 4 re\$licates at the central \$oints and 4 a0ial \$oints WP A %28%# and !' 4actorial \$oints Table %#. The e0\$eriment data ? ere adMsted to a second order \$ol3nomial model D5.)# to \$redict the behavior o4 N9 C db#, TC concentration m1/%" 1 o4 sam\$le# and T6C m1 CAD/%" 1 o4sam\$le#.

$$\varphi = \beta_0 + \sum_{i=1}^2 \beta_i \lambda_i + \sum_{i=1}^2 \beta_{ii} \lambda_i^2 + \sum_{i=1}^2 \sum_{j=1}^2 \beta_{ij} \lambda_i \lambda_j + \varepsilon \quad (7)$$

R here X is the res\$onse variable, S_0 is a constant number, S_i , S_{ii} and S_{ij} are the linear, 5uadratic and cross coe4icients, res\$ectivel3. Y_i and Z_M are the levels o4 the inde\$endent variables and the error is re\$resented b3 [. The adMstment to the model is inter\$rated b3 the correlation bet? een the 4actors and the res\$ponses throu1h the coe4cient o4 determination R^1 #. The more si1ni4icant combinations o4 4actors in the model ? ere identi4ed usin1 an AN- 8 A variance anal3sis \$\' .\'\'\' , #, usin1 9 initab %\'\'\' statistical so4? are 9 initab] %\'\'\' , 9 initab *nc., 6A, U(A#.

3. Results and discussion

3.1. Drying "inetics

*n dr3in1, ? et material is sub1ected to the action o4 a hot and dr3 air stream, ? hich eva\$orates the moisture and increases the humidit3 o4the air J% % K The \$rocess ends b3 reachin1 moisture e5uilbrium, ? hen the va\$or \$ressure o4the solid's moisture e5uals the \$artial \$ressure o4the 1as stream J! " K The dr3in1 time di4tered in each e0\$eriment

Table %

D0\$eriment values and res\$onse variables 4or central com\$osite rotatable desi1n CCRD#

N°	Code	TA !°C"	# A !m.s1"	Res\$onse 8ariables		
				1' MC !("	2TC	3T) C
%	(8, 08	2, %	2 8#	.) A" .! !	%8.1 A%68	+) .%A1.2
!	(8, 08	2, %	8 %	.) 4 A" .%#	%4, A%6%"	+4.) A1."
+	(8, 08	4, 8#	2 8#	).' , A" .%8	%8 ." A%6, %	,' .4A' .)
4	(8, 08	4, 8#	8 %	).' ' A" .4%	%! .+A" .4"	!' ." A%4
,	(8, 08	,, "#	8.4% V#	).' +A" ."	%4%! A" ,'	4' .4A1."
2	(8, 08	,, "#	,, 8 8#	.) ! A" .4	%! .9A" .2+	4" .) A%6%
)	(8	2' .%4	) "#	.) 8! A" .2	%% .) A" .8,	4% A%!
8	(8	4%64	) "#	.) 8! A" .%	%% .2A" .8,	!) .) A%"
,	(8, 08	,, "#	) "#	2.% A1 .+2	%4' .% A%!,	%) +A+.4
%	(8, 08	,, "#	) "#	2.+4A" .%	%4% A%+!	!) ! A1.!
%6	(8, 08	,, "#	) "#	2." 2A" .%4	%4%8A" .8%	%) , A) .)
%4	(8, 08	,, "#	) "#	2.% A" .4	%4" .2A" .2)	4.2A1.!

*N9 C, Nnal moisture content B #, 1TC, total carotenoids 1/%" 1 o4 (am\$le# 1T6C, total Shenols m1 CAD/%" 1 o4sam\$le#

(ource: The Authors

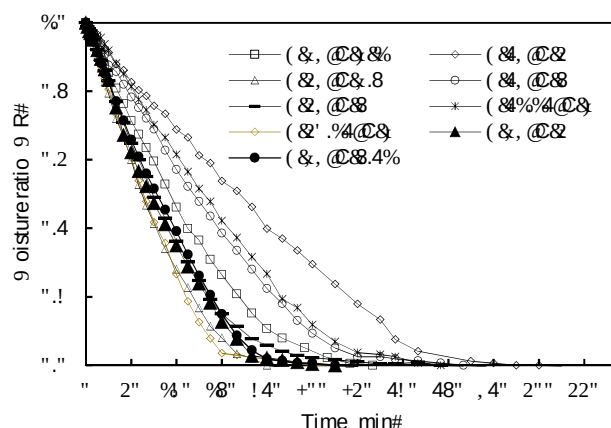


Figure 1. Moisture ratio as a function of drying time (source: The Authors)

since the process was stopped when there was no change in the weight of the sample, for example, a sample in sample with initial moisture of 82.28 A. (2) B as subjected to drying at 40°C and an air velocity of 0.2 m/s, with a time to reach moisture equilibrium of about 10 min; while, at a temperature of 42°C and air velocity of 0.2 m/s, the time was 10 min, achieving a 90°C of 42.0 A. (4) and 0.8 A. (2) B, respectively, evidencing that an increase of 2°C in the drying air temperature represented a change of about 20% of the percentage points in the moisture and 2 min less in the drying time. These results are comparable with those reported by Jørgensen (2004) who dried samples at 40, 45, and 50°C with initial moisture of 0.8, 0.9, and 1.0, respectively, reaching a final moisture of 0.2, 0.3, and 0.4, respectively, in a time of 10, 15, and 20 min, respectively.

Nevertheless, the moisture ratio (g/g) changes with respect to the drying time at different temperatures, curves that are comparable with studies carried out on commercial samples, typical behaviors of the drying curves. As for the decrease of the moisture ratio (g/g), this is proportional to the change in the weight of the sample. Therefore, low g/g values indicate small changes in the recorded weight of the sample in relation to time. The moisture ratio decreases as the drying time passes, however, for a same point in time, the g/g can be different because of a change in temperature or change in air velocity, evidencing more relevant changes from the effect of temperature.

3.2. Effective diffusivity and activation energy

In Figure 1, En values (g/g) versus drying time are presented for three TA(conditions, rounded to 8 A(factor) m/s. A linear trend was observed at the beginning of the drying as a result of the sample drying during the period of constant drying, indicating that the phenomenon is controlled by diffusion (Jørgensen, 2004).

It is also possible to establish the dependence of En (g/g) on TA(by observing the slope of the curves since it increased with the increase in the TA((Figure 1). Here, the slope of the curves decreased with the decrease in temperature, independent of A(; this difference is reflected in the increase of moisture diffusivity in the samples.

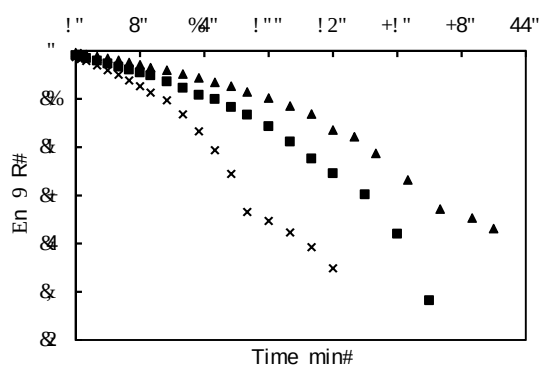


Figure 2. Moisture ratio as a function of drying time (min) of the sample in an air velocity of 0.2 m/s (Δ) 40°C, (□) 45°C, (○) 50°C (source: The Authors)

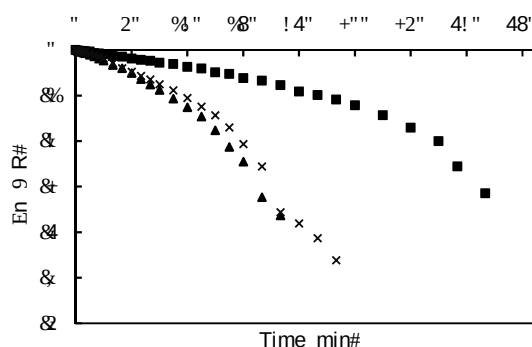


Figure 3. Moisture ratio as a function of drying time (min) of the sample in an air velocity of 0.2 m/s (Δ) 40°C, (□) 45°C, (○) 50°C (source: The Authors)

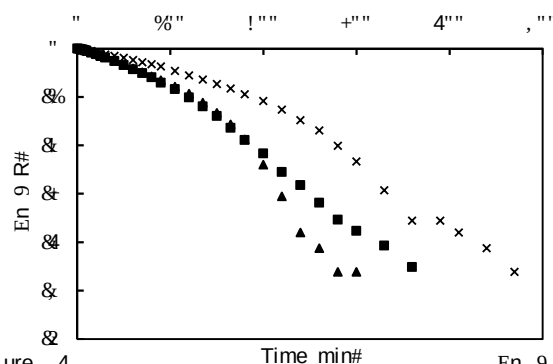


Figure 4. Moisture ratio as a function of drying time (min) of the sample in an air velocity of 0.2 m/s (Δ) 40°C, (□) 45°C, (○) 50°C (source: The Authors)

The behavior was similar when the experiments were rounded to 8 A(factor) m/s. Table 1. This behavior coincides with studies performed by Jørgensen (2004) for drying samples with different geometries. As for the result of the curves obtained when plotting En (g/g), these results did not present a typical behavior of straight lines during the period, possibly affected by the rehydration blanching since this behavior is comparable to the one presented by Jørgensen (2004) who studied different rehydrations before drying samples in temperatures of 40, 45, and 50°C.

Table 4.

Analysis of variance for the final moisture prediction model

Source	MC			CT			TC		
	2	3	4	5	6	7	8	9	10
Model	4	2.4	1.2	0.8	0.5	0.3	0.2	0.1	0.0
Error	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	5	2.5	1.3	0.9	0.6	0.4	0.3	0.2	0.1
TA(°C)	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
8 A(m/s)	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Quadratic	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
TA(°C)	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
TA(°C)	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
8 A(m/s)	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
8 A(m/s)	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Error	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	5	2.5	1.3	0.9	0.6	0.4	0.3	0.2	0.1

(. sum of squares

(source: The Authors

$$TPC = -37459 + 484.4(TAS) - 4.337(TAS)^2 - 526.0(VAS)^2 \quad (10)$$

To visualize the combined effects of the factors on the response variables, the response surfaces and the contours were generated for each of the adjusted models that predicted the behavior of each response variable as a function of the independent variables. The effects of drying air temperature and air velocity on MC, TC and T6C were seen for the evaluation of these diagrams.

The effect of TA(and 8 A(on MC in the dehydrated sum\$>in as significant and ranked from 2.2 to 2.1 B, evidencing a significant difference between temperature and air velocity. On the other hand, the analysis of variance of the proposed model for final moisture prediction had a probability value of 0.000, less than WP 0.05, Table 4#, indicating that the model is highly significant and could be used for the determination of final moisture in dehydrated sum\$>in and the lack of fit as not significant. So, as the above, the model is represented in the design, which is appreciable in N1. , 8, here, at temperatures near to 4, 6 and 2, 6 and air velocity of 2 and 8 m.s⁻¹; the moisture was higher compared to the area of the surface around 4, 6 and 2 m.s⁻¹. This is because the high temperatures during the drying did not achieve a greater reduction of moisture, which is explained as a function of the model coefficients.

3.4. Total carotenoid content (%)

For the carotenoid model, the probability value was highly significant, b 0.000, # Table 4#, ranked from 0.2 A to 0.8 A. 0.8 m1/%" 1 of sample. The model is represented in the response surfaces N1s. , 8 and, 8 for the total carotenoid content; in addition, the drying rate favored the retention of carotenoids. These results are comparable with studies by J%Kon the reduction of the beta-carotene content in samples subjected to heat treatment at 10° 2" 6# and high 8", 8", 1" and 0" 6# temperatures for 1 h, with results of 4.4%, +0.1/1 and 8.0%, 1.1, 4.82 and 4.0% m1/1,

respectively.

Moreover, temperatures above 10° led to an increase in the total carotenoid content, as compared to the temperature 4, 6, perhaps because of a higher availability of these compounds since the heat treatment inactivates the oxidative enzymatic activity, also causing a break of some structures and leading to a higher concentration of beta-carotene. In addition, the loss of moisture means that soluble solids are more concentrated in the sample.

3. Total phenolic content (%)

Table 5 shows the content of total phenols present in the dehydrated sum\$>in, which varied from 1.1 to 1.9 A. 1.1 m1 CAD/%" 1 of sample. It was found that a higher concentration of phenolic compounds was observed at 4, 6 and 2 m.s⁻¹, but the results obtained were 4.2 A. 1.1 m1 CAD/%" 1 of db, with +2 A. 8 and 1.8 A. 8 m1 CAD/%" 1 of dr3 sample in samples of sum\$>in of Cucurbita moschata. It is possible that this difference was due to the influence of the storage process and storage since phenolic compounds can be formed during the process from the availability of precursors of phenolic molecules or by non-enzymatic interconversions between them. It is also, immersion in water at temperatures above 10° 6, as done during blanching, can be attributed to losses of some phenolic compounds by leaching. It is 4K.

In this experiment, at temperatures higher than 4, 6, the total phenolic content decreased, with concentrations of 0.1 to 0.2 A. 1.2 and 4% A. 1.1 m1 CAD/%" 1 of sample obtained at 2, and 2' 6, respectively, changes that indicate the influence of temperature on the phenolic content. (Similar results were obtained by J, K !). A 0" m1 CAD/%" 1 of sample in Cucurbita pepo with 0.1, m1 CAD/%" 1 of dr3 sample, as quantified in four obtained at 0" 6, in contrast to temperatures close to 4" 6, probably because of the release of phenolic compounds bound to cellular structures with that level of thermal energy, provided by the drying treatments. It is 4K.

4. 5 optimal drying conditions

In the search of optimum conditions, the minimum and maximum response method for total carotenoids and phenols was used, based on predictive models obtained in a composite central design. The following conditions were obtained: 2.1 B for moisture at 4, 6 and 2 m.s⁻¹; carotenoid concentration 0.4% 8" m1/%" 1 sample at 4, 6 and 2 m.s⁻¹; total phenol concentration 4.2 m1 CAD/%" 1 sample at 4, 6 and 2' m.s⁻¹. Thus, the optimum drying points for the sum\$>in of sum\$>in were 4, 6 and 2 m.s⁻¹, conditions in which the drying time could be approximately 3, 2 to 2 hours, with minimum moisture between 2 and 2 B, suitable for obtaining a commercial flour and subsequent products based on sum\$>in of sum\$>in such as pasta, biscuits, baked foods, and fiber supplements, among others, with moisture at 0.1, 4 A. 1 B, 0.24 A. 1.1% and 0.1 A. 0.2 B. It is 1, 1, 8) K.

4.1. Drying efficiency (%)

The dr3in1 e44cienc3 c#? as calculated usin1 D5. %%, the ener13 e44cienc3 ? as calculated in the ran1e o4' ". "" to ' !.' +B 4or the dr3in1 o4the Sum\$>in Sul\$ in the dr3er tra3.

$$\eta = \frac{W - W_s}{W (X_i)} * 100 \quad (11)$$

The ma0imum e44cienc3 \$ercentale ? as ' !.' +B, ? hich corres\$onded to the o\$timum dr3in1 conditions , , @ and) m.s%# ? hile the e44cienc3 ? as lo? er com\$ared to the other e0\$eriments under dr3in1 conditions at 2, @ and 2m/s ? ith an e44cienc3 o4' ". "" B. *n 1eneral, the e44cienc3 did not \$>resent si1ni4cant di4ferences since, in all o4 the e0\$eriments, the value e0ceeded ' "B ? ater removal. 9 oderate tem\$eratures, si1htl3 hi1h air velocities, and averale \$rocessin1 times are needed to increase c. *n this stud3, a hi1her tem\$erature si1ni4cantl3 a4ected the heat losses because o4the insu44icient insulation and hermetics o4 the dr3er tra3. The e4fect o4the air velocit3 on the heat losses ? as less than the e4fect o4the tem\$erature; in addition, the increase in the air velocit3 caused an increase in the c.

Conclusions

The o\$timum conditions 4or air dr3in1 Sum\$>in based on the variables TA(@# and 8 A(m.s%# to reach ? ere , ,) @ and)." m.s%#res\$ectivel3. These conditions also led to a hi1her concentration o4 total carotenoids, \$henols and moisture lo? er than 2B in s5uash 4our, ? hich can be used to ma>e various \$roducts such as \$asta, biscuits, candies, and ba>ed foods.

The calculated e4fective di44usivit3 values varied bet? een , . "% % & and %), ` % & m !. s.&in the ran1es o4the TA(and 8 A(. *ncreases in the e4fective di44usivit3 and decreases in the activation ener13 resulted 4rom the tem\$erature increases, and the de\$endence o4tem\$erature on the di44usivit3 coe44icients ? as described b3 an Arrhenius t3\$e relationshi\$. These t3\$es o4 \$ro\$erties, includin1 di44usion o4 moisture and activation ener13, should be studied 4or each cro\$ because there is not much in4ormation available 4or their determination.

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- J! K A3din, D. and Cocmen, D., The in4uences o4 dr3in1 method and metabisul4ite \$re&treatment on the color, 4unctional \$ro\$erties and \$henolic acids contents and bioaccessibilit3 o4Sum\$>in 4our. ER T & Nood (cience and Technolo13, 2", \$! +8, &' ! , ! "% . D- * % % 442/M? t.!"%4."8."! , .
- J+K 8 alleld, N, Taena, D., - rti< (, Dstrada, * and Tobar, D., Una\$al& Dorado, Sum\$>in ne? cultivar ? ith hi1h dr3 matter 4or 4resh consum\$tion. Acta A1ronGnica, , ' , \$! %) &44, ! "% . D- * % % 442/aca1
- J4K R an1, (, Don1, = and V3un1, T., 6h3sicochemical \$ro\$ert3 o4 Sum\$>in slices deh3drated ? ith red al1ae e0tract. =ournal o4 the Vorean (ociet3 4or A\$\$lied Tidlolical Chemistr3, , 4, \$! . ' ! %&' ! , , ! "% D- * % %) /TN+!, +9&%

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4ner02 consum\$tion and 5ualit2 o6 service in 7 8 AN- A \$erformance evaluation bet9 een cross&a2er and)4448"! .%+.4

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Abstract

Different communication schemes for 7 ireless 8 od2 Area Net9 orAs 7 8 AN# \$retend to achieve a fair tradeo66 bet9 een efficient ener02 consum\$tion and the accom\$lishment o6 \$erformance metrics. Among those schemes are the Cross&a2er \$rotocols that constitute a 0ood choice to achieve the aforementioned tradeo66 b2 introducing novel \$rotocol techni\$ues 9 hich are a9 a2 from the traditional communications model.)n this 9 orA 9 e assessed the \$erformance o6 a 7 8 AN cross&a2er \$rotocol stacA b2 com\$arino it a0ainst the \$erformance o6 the \$rotocols o6 the)4448"! .%+.4 standard, 9 hich is commonl2 used for 7 8 AN de\$lo2ment no9 ada2s. 7 e evaluated the \$erformance o6 both, cross&a2er and)4448"! .%+.4 a\$roaches, b2 means o6 a simulation, b2 usino a \$o\$ular net9 orA simulator and its frame9 orAs for 9 ireless net9 orAs. And then \$erformed a statistical com\$arison and ascertained that the cross&a2er \$rotocol stacA offers better \$erformance re0ardin0 a tradeo66 bet9 een efficient ener02 consum\$tion and \$erformance metrics in our \$articular test scenario. 7 e observed that, in 0eneral, the cross&a2er a\$roaches out\$erformed both modes o6)4448"! .%+.4 standard slotted and unslotted# re0ardin0 ener02 consum\$tion, end to end dela2, \$acAet loss rate and 0ood\$ut. The results o6 our e/ \$eriments re\$orted that the cross&a2er strate02 saves u\$ to 8" B more ener02 than)4448"! .%+.4 unslotted and it is onl2 a +B bel09 the slotted mode. Re0ardin0 the 5ualit2 o6 service metrics the \$erformance 9 as a 9 a2s better 9 hen usino the cross&a2er scheme.

Ke ! ords- Communication \$rotocols; Cross&a2er schemes; 4ner02 consum\$tion;)4448"! .%+.4; , C NeTDD; Eualit2 o6 service; 7 ireless 8 od2 Area Net9 orAs.

Consumo de ener0Ia 2 calidad de servicio en redes 7 8 AN- Una evaluaci?n de desem\$eGo entre ca\$a cru@ada e)4448"! .%+.4

Resumen

Dentro de los es\$uemas de comunicaci?n de redes inalHmbricas de H\$ea cor\$oral 7 8 AN# se encuentran los \$rotocolos de ca\$a cru@ada, constituidos en una novedosa o\$ci?n \$ara alcan@ar un balance efectivo entre consumo eficiente de ener0Ia 2 mlticas de desem\$eGo. 4n el \$resente trabajo, evaluamos el desem\$eGo de una estrategia de ca\$a cru@ada al com\$ararla con los \$rotocolos del estHdar)4448"! .%+.4 en una 7 8 AN. ' e evalu? el desem\$eGo de ambas estrategias em\$leando una simulaci?n de redes 7 8 AN. Kue0o se ejecut? una com\$araci?n estadistica 2 se encontr? Sue la estrategia de ca\$a cru@ada ofrece un mejor desem\$eGo con res\$ecto a la comensaci?n entre consumo eficiente de ener0Ia 2 al 0unas mlticas de desem\$eGo en nuestra 7 8 AN. , bservamos Sue en 0eneral, la estrategia de ca\$a cru@ada su\$era a ambos modos del estHdar)4448"! .%+.4 ranurado 2 no\$anurado# con res\$ecto a consumo eficiente de ener0Ia, retraso e' tremo a e' tremo, tasa de \$I r0ida de \$a\$uetes 2 0ood\$ut.

" alabras clave- Calidad de servicio; Ca\$a cru@ada; Consumo de ener0Ia;)4448"! .%+.4; , C NeTDD; Lrotocolos de comunicaci?n; Redes inalHmbricas de H\$ea cor\$oral.

1. Introduction

The develo\$ment o6 7 8 ANs, s\$eci\$al2 9 hen used in health monitorin0 a\$li\$ations, \$aces im\$ortant challen0es and tradeo66s re0ardin0 net9 orA ener02 consum\$tion batter2 de\$letion# and accom\$lishment o6 5ualit2 o6 service. E o' #

metrics. 7 8 ANs are to be de\$lo2ed on and inside the human bod2. Mence, the most common tradeo66s in usino 7 8 ANs for medical monitorin0 are related to malfunctionin0 induced b2 the conte/t and scenario o6 de\$lo2ment, as 9 ell as im\$lementation constraints im\$osed b2 the human bod2 tissues- %#the use o6 lo9 \$o9 er levels to avoid tissue heatin0

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and reduce levels of electromagnetic absorption, the need for high levels of quality of service. Eo' guarantees for the management of critical information, such as the health condition of a patient, the size of sensor node devices to avoid user's experience discomfort, the heterogeneity of the sensor nodes, communication channel variations, due to the mobility of the sensor nodes in the WBAN, introduced by body structural changes, and the scarce energy resources that depend on the battery life.

Current state of the art [94] shows that most of the research in WBAN has focused on balancing the tradeoffs between energy consumption and maintaining acceptable levels for Eo' metrics. Current techniques and approaches regarding this issue have been proposed, most of which emphasize finding the best settings and configurations in medium access schemes at CAC Medium Access Control layer, specifically CCA/CA Carrier Sense Multiple Access Collision Avoidance strategy both slotted and unslotted modes [95]. Current implementations of such approaches can only be tested using legacy communication technologies such as 4448 [96]. 4 GPP standard for Wireless Personal Area Network or LAN.

Although 4448 [96] offers good support for WBAN implementations, it has been noticed that hierarchical layered protocols are not a good choice to balance the energy and Eo' tradeoffs existing in Wireless Sensor Network or WBAN. As a consequence, a new type of approach appeared in WBAN scenario, namely cross-layer design [97], which proposes communication between non-adjacent layers of communication stacks in order to devise strategies that improve the performance in terms of energy consumption and Eo' accomplishment. This approach, however, introduces additional complexity in the design and implementation of the WBAN.

This paper presents the results of a comparison between 4448 [96] and a novel cross-layer strategy presented in [98], focused on the balance of energy and Eo' tradeoffs in a simulated WBAN application scenario. The comparison is performed using a scenario simulated in, C N4TDD [99].

This article is organized as follows: section 2 presents a contextualization and related work; section 3 presents the design of experiments setup, the WBAN simulation setup, and development in, C N4TDD. In section 4, we show the results and analysis of the experiments, and finally the conclusions are presented in section 5.

2. Context and related work

2.1. IEEE 802.15.4

4448 [96] is a standard that deals with the intersection among legacy communication, legacy data rates, and legacy cost devices in WBAN. This standard specifies the physical layer and medium access control layer of the communication model [see Fig. 1]. The PHY defines mechanisms for the activation and deactivation of radio transceivers, channel energy level detection, received packets link quality indication, Clear Channel Assessment CCA of the CCA/CA protocol, and transmission reception of

packets.

The MAC layer is in charge of channel access, maintaining a reliable link between devices, synchronizing, associating and disassociating devices, and implementing a protocol for medium access control. There exist two mechanisms for medium access: beacon-enabled slotted CSMA/CA and non-beacon-enabled unslotted CSMA/CA.

In non-beacon-enabled medium access, nodes always listen to the channel and perform transmissions once they find it to be idle. Nodes can detect a collision when they do not receive an acknowledged packet ACK from the receiver of the transmission.

In beacon-enabled medium access, a central device announces as network or coordinator periodically sends a beacon message used to synchronize the network and to assign the transmission time slots for every node. Nodes contend for these time slots in the Contention Access Period CAP and enter sleep mode for energy saving purposes in the inactive part of the superframe [see Fig. 2].

2.2. Cross-layer design

Cross-layer design basically performs a violation of the layered hierarchy by allowing protocols from non-adjacent layers to exchange information and relevant parameters obtained at runtime. The cross-layer approach proposes various alternatives to the traditional layered model. The creation of new interfaces to manage the connection and the flow of information among layers [see Fig. 3a], the merging of adjacent layers, where a new superlayer is created by merging services provided by two or more layers [see Fig. 3b], vertical calibration across layers, setting a priori information obtained from them or updating it based on parameters at runtime [see Fig. 3c], new abstraction,

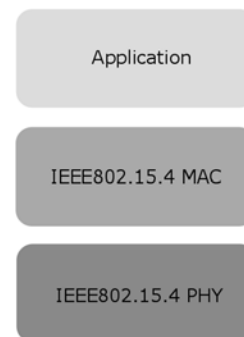


Figure 4. IEEE 802.15.4 layers stack.
Source: The authors

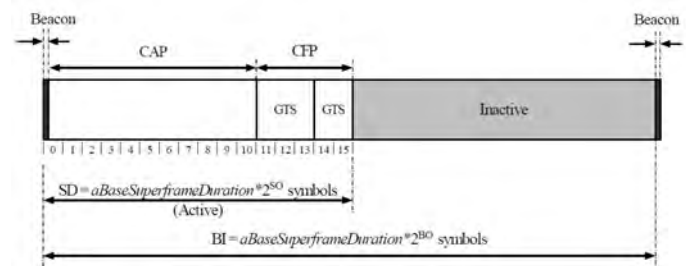


Figure 5. IEEE 802.15.4 slotted mode superframe.
Source: The authors

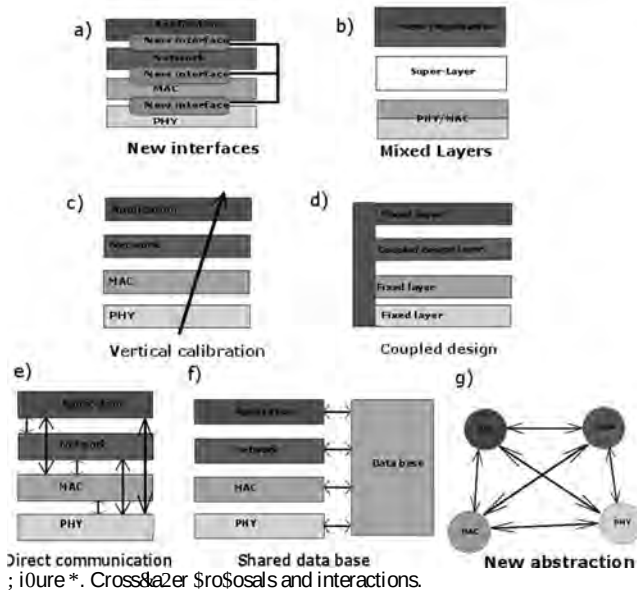


Figure 3. Cross-layer protocols and interactions.

which defines a non-layered architecture to have functions similar to those of the traditional protocol stack. See; i.e., [10]. Implementations of the cross-layer approaches have also been proposed based on direct communication between layers with channels of information between layers performed at runtime, and a shared database across layers with a new layer-like scheme that performs the storage and retrieval of layer-related information, and a complete new abstraction innovative implementations aimed at replacing the traditional stack-like scheme [11, 12, 13, 14].

2.3. Cross-layer protocol

The novel cross-layer technique for WBANs presented by Nabi et al. [15] is built upon the premises of avoiding dependence on network protocols or network layer schemes for scheduling for a given node; instead, using a TDMA Time Division Multiple Access scheme as medium access strategy to avoid common energy-related issues present in contention-based schemes; and to adapt transmission power, since lower power levels do not always ensure energy efficiency.

For routine duties, nodes in the network are supposed to have enough space in memory to store data items from neighboring nodes so each node broadcasts its own data item and at least a data item from another node; this strategy is called Synchronization. The power adaptation mechanism makes the calculation of two metrics, one metric is concerned with outlining a quality Q_i and the other one prevents cluster formation when outlining a quality improves among neighbors; hence it maintains a link to the sink node for every node in the network. This strategy cooperates with mobility. Given that isolated/disconnected nodes increase their transmission power to reach neighbors and reconnect to the network, because in isolation both metrics decrease consequently.

The authors claim that the aforementioned scheme ensures efficiency in energy consumption as it prevents

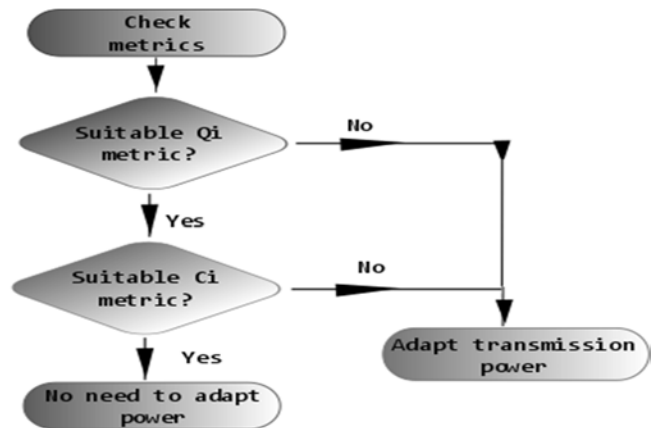


Figure 4. Cross-layer protocol power adaptation mechanism.

retransmissions. Besides, data routing does not depend on the topology because the nodes broadcast information without concern for the relative position of the intended receiver, and simultaneously, the latency is reduced because all nodes can reach the sink using the power adaptation mechanism. They also consider that the strategy needs to optimize listening on active time slots to reduce the consumption caused by idle listening.

Figure 4 illustrates the power adaptation mechanism of the protocol for AS.

2.4. Energy consumption and QoS in WBAN

The tasks performed by nodes in a WBAN, and in general, in any WSN, include sensing, data processing, and communications incur in energy consumption. The wireless communication process constitutes the major power consumption task. As nodes implanted on or designed around the body have a very small form factor ensuring user comfort, batteries to power these devices are as small, and hence energy storage capacity becomes a relevant issue. Cost applications of WBANs restrict nodes to avoid requiring replacement of the battery over long periods of time; for example, a pacemaker or a glucose monitor is supposed to last for at least 2 years. Thus, energy-related strategies have to be devised to assist nodes in a WBAN for the required period of time. The network lifetime is defined as the time between the moment the entire WBAN is turned on and the moment that the first node runs out of power, so energy-saving strategies should sort uniform energy drain, focusing on balancing power consumption among all the nodes comprising the network.

Another important issue is the constraint related to R; power, namely the consequences of the body's reaction to electromagnetic radiation, and the localized specific absorption rate in the body. To show the magnitude of the situation, sensors in a WBAN are required to broadcast data at lower power due to heating of the radio chips, transferring heat to the tissues that form the muscles and causing harm to the WBAN user burnings or even malignant cell degeneration [16].

Besides the aforementioned issues, several causes of

energies have been identified in WSNs, including collision, overhearing, idle listening, over-sampling, control packet overhead, and traffic fluctuations. Collisions occur when two or more nodes try to access the communication channel simultaneously. Idle listening is when a node listens to a channel lacking traffic. Overhearing occurs when nodes receive packets that are not intended for them. Control packet overhead happens when a node adds too many control headers to the payload. In addition, over-sampling means that many retransmissions are required for a packet to reach its destination [10].

Energy guarantees in WSNs need special attention given the context of application of this type of network; for instance, in medical environments, sportsmen and soldiers vital signs monitoring. Although WSNs as a subset of WNs face the same technical challenges of most wireless networks, it is important to notice that the critical levels regarding issues like network connectivity, security, delay, energy consumption, packet delivery, traffic prioritization, and bandwidth allocation are more demanding in WSNs [10].

In this research, we pretend to compare two protocols for WSN, a cross-layer scheme for WSN and 4448 [11]. We focused on the trade-off between energy efficiency and energy accomplishment in both protocols. The following three energy metrics are in the scope of this work: 4th to 4th Delay, Packet Delivery Ratio, and Goodput as the three overall major requirements in WSN transmissions.

3. Methodology

Three fundamental steps were performed to achieve the comparison between the protocols: first, to define an experiment to evaluate the performance of both communication schemes. An experimental unit was proposed, together with a set of factors, treatments and their corresponding levels, and a set of response variables; then, to simulate the protocols in a WSN test scenario, taking into account channel propagation models for the wireless links and a mobility model for the nodes and the network; finally, to gather the results obtained from the simulation and to perform a statistical analysis to compare the performance of both communication schemes.

3.1. Experimental design

The experimental design is a necessary stage to achieve the goal of a fair comparison between the protocols for WSN. The main focus of our work is to assess the energy consumption in both protocols and analyze which of them is more suitable for WSN, given the constraints introduced by the management of the battery. This analysis, however, is not enough since there is a trade-off between energy consumption and acceptable energy metrics in the context of WSN. Hence, the evaluation was aimed to reveal which communication scheme had the lowest energy consumption and the best energy accomplishment.

The experiment was devised as a model of different effects, in which we chose all the treatments. The results and conclusions

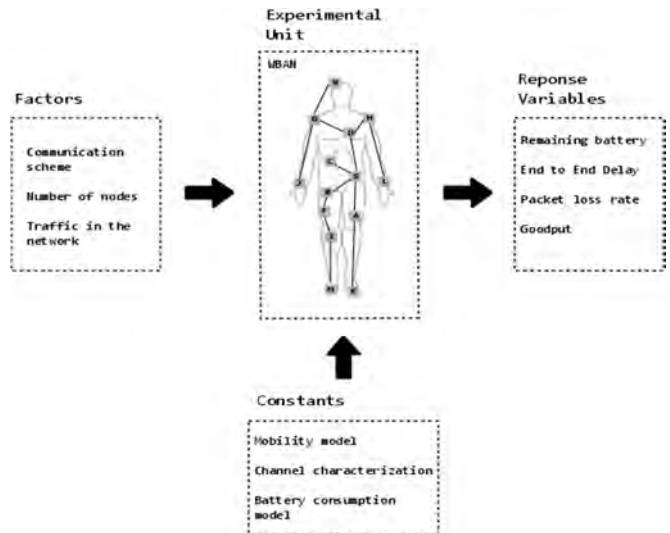


Figure 4. Experimental unit, factors, constants, and response variables of the experiment.

Source: The authors

are assumed to be tightly tied to the levels of each factor involved in the experiment. To conclude about the results of the experiment, we proposed a set of hypotheses. A major requirement of the experiment was to run a fixed number of replicas of each treatment to include the effects of variability induced by nuisance factors and run these replicas randomly to make the environment of treatment execution as uniform as possible as in completely randomized experimental designs [12].

4. Experimental unit

The experimental unit is a wireless body area network comprised by the following components, as shown in Figure 4: a node and a few sensor nodes installed on a patient's body. All of the nodes have specifications based on the TinyCC-4 radio module, whose model is available in CC-NetDD; a wireless channel model to simulate induced attenuation and signal shadowing; a mobility model used to simulate the patient's movement. We used C-AN [13].

4.1. Factors

The factors listed below were considered to have significant influence on the response variables as they represent the main characteristics of the WSN itself and also by taking an experimental reference frame for wireless networks from [14].

- Communication scheme protocol: This factor has two qualitative levels, one corresponds to the cross-layer protocol and the other one to protocols of the 4448 [11] standard.
- Number of nodes: We considered this factor to have direct incidence on energy metrics and energy consumption, given that network connectivity could be impacted by the amount of neighbors surrounding individual nodes and the distance between them. Two levels were defined for this factor, networks of 10 and 20 nodes.

Table 4

Experiment treatments

Communication scheme	Number of nodes	Traffic in the network
Cross-layer Nabi et al.	+	M0h Ko9
	%	M0h Ko9
4448"!.%4	+	M0h Ko9
Unslotted & slotted	%	M0h Ko9

Source: The authors

- Traffic in the network. As we wanted to observe the energy consumption in the 7.8 AN, we considered that the amount of traffic could have a direct impact on battery management in wireless transmissions. We defined two levels for this factor, as follows: one level corresponds to heavy traffic: nodes transmitting every 200 seconds and low traffic: transmissions are performed every 20 minutes or 1200 seconds.

As shown in Table 4, the treatments of the experiment are all combinations of all levels of the factors, and every treatment is repeated 10 times in the experiment. As referred before, the replication order is randomized in order to avoid dependence and uniformity between treatments.

*.%. Res\$onse variables

As we decided to evaluate the tradeoff between energy consumption and Eo' performance, we chose the following response variables: Remaining battery, Latency, Deliver2 Ratio, 4nd to 4nd Delay, and Goodput, since these performance metrics satisfy all major requirements in 7.8 AN scenarios, namely: Ko9 delay data transmission, low packet loss rate, accurate and reliable transmissions, and low energy consumption. The variables are defined as follows:

- Remaining battery- It is the average percentage of energy available at the battery of the nodes, once the simulation finished.
- Packet Loss Ratio- It is the average rate percentage of packets lost in the entire simulation. It is calculated as the ratio between all the packets received at the sink and the packets sent to all nodes in the network.
- 4nd to 4nd Delay- It is the average latency experienced by packets transmitted from a sensor node to the sink. It is obtained as the ratio between the total delay of all the packets that successfully reached the sink and the number of packets received by the sink.
- Goodput- It is analogous to the number of successfully transmitted bits of information per unit of time. It is calculated as the ratio between all the bits successfully received at the sink and the total time of the simulation run.

*.%. 4/ Experiment hypotheses

As the focus of our experiment is to identify which protocol exhibited the best performance in the satisfaction of

the balance between energy consumption and Eo', the null hypothesis is always the same for every response variable. Our hypothesis is hence that the mean value of the response variable is the same no matter what protocol is applied to the 7.8 AN scenario and equal to 0. The set of hypotheses is formalized below:

- Cross-layer protocol α_1 exhibits a better performance regarding average energy consumption than 4448"!.%4 standard α_2 , where α_i is the average remaining battery load of all nodes in the network.

$$H_0: \alpha_1 > \alpha_2$$

$$H_1: \alpha_1 < \alpha_2$$

- Cross-layer protocol β_1 exhibits a better performance in end-to-end delay metric than 4448"!.%4 standard β_2 , where β_i is the average time elapsed in a successful packet transmission from node to sink.

$$H_0: \beta_1 < \beta_2$$

$$H_1: \beta_1 > \beta_2$$

- Cross-layer protocol γ_1 exhibits a better performance in packet loss rate metric than 4448"!.%4 standard γ_2 , where γ_i is the average rate of packets lost during the entire simulation run.

$$H_0: \gamma_1 < \gamma_2$$

$$H_1: \gamma_1 > \gamma_2$$

- Cross-layer protocol δ_1 exhibits a better performance in Goodput than 4448"!.%4 standard δ_2 , where δ_i is the average quantity of bits transmitted per second.

$$H_0: \delta_1 > \delta_2$$

$$H_1: \delta_1 < \delta_2$$

3.2. Simulation setup

The simulation tool used in our work is, C-NetTDD, a modular discrete event simulator that is suitable for telecommunication networks and protocol simulations. The network can be modeled using N4D-Net/ORA-Description/Interface and the behavior of protocols and modules is coded using CDD. C-NetTDD has a special framework for wireless network simulation called CIVIC-OP, which provides useful built-in modules and models, like battery, channels, packets, messages, mobility, LMY, CAC, Network and Application layers, and several examples for wireless networks.

*.%. Cross-layer protocol setup

For the implementation of the cross-layer protocol, we had to work on three layers: LMY, CAC, and ALL since the network layer functionalities are assumed by the SOSTINOT strategy as described by the authors of the protocol. The cross-layer protocol is divided into 1 step: when a node has to transmit, it first checks its memory to include a data item received from a neighbor in a previous transmission

round and its in a message of the last transmission round a register to count the neighbors from which a node received packets in the last transmission round. All nodes broadcast, no unicast transmission is performed; if, once data is received, the new data items replace the existing data items in memory and the in a message is updated, as well; if it is decided that before going to sleep in the superframe, every node had to calculate metrics taken into consideration the last transmission rounds. After metric calculations, the nodes had to check the metrics to decide whether to increase/decrease TV slot or not; if, or every packet contained data items generated at the ALL layer, a control info is added to alert the CAC layer if TV slot has to be increased/decreased; if through another control message, the CAC layer notifies the LMY layer the TV slot level for the transmission; if with the TV slot level, the LMY layer calculates the consumption in the transmission.

The LMY layer has implemented using an existing module of CiviC, although some changes to the original files were performed in order to include the functionality that allows the cross-layer nodes to change among the different levels of transmission slot and their corresponding current battery consumption. The LMY layer decoder and signal modulation were set according to the TCC-4 radio specifications. Specific levels for TV slot are detailed in TCC-4 datasheet. Parameters were defined: "m7 & +d8 m", "m7 & +d8 m", "m7 & +d8 m", and "m7 & +d8 m". Regarding on the wireless channel, we used the simple path loss and lognormal shadowing analytical models; for the 7.8 GHz channel characterization, we chose a value of +3 for the path loss coefficient to consider NLOS, Nonlinearity, and multipath transmissions as well. Parameters of 1.3 and 0.06 for the mean and the standard deviation of the lognormal distribution were used.

A TDC A medium access scheme at CAC layer has implemented by modifying an available TDC A CAC provided by A. Kumar in [3], by the addition of the corresponding functionality to change transmission slot among different levels, in order to inform the LMY layer of the change in TV slot. Each node in the cross-layer protocol has assigned one time slot of 64 ms length in a 2 second TDC A frame.

The cross-layer protocol Application layer has implemented using a built-in sensor application available provided in CiviC; we took advantage of the existing functionalities and added the corresponding methods

required for the calculation of the cross-layer protocol metrics out of a quality and connectivity to the target area. We implemented vectors to record the in a message, methods for metrics calculation and checking, and a control info message to inform the CAC layer and change on TV slot level. An important issue to mention is that we had to implement a node needs help packet, once a node had increased TV slot level in consecutive times and the metrics remained poor because the other nodes had good metrics, stopped increasing slot, and could not reach this particular node. This node needs help packet alerted good metrics nodes to increase slot again to reach isolated poor metrics nodes.

Figure 4 shows the results of the 4 models available in C-NetDD framework and modified the original code and the simulation settings. We also introduced the necessary adjustments to the 802.11n mobility model, as well.

We used the existing 4 models available in C-NetDD framework and modified the original code and the simulation settings. We also introduced the necessary adjustments to the 802.11n mobility model, as well.

Statistical analysis of the results

In the planning phase of the experiment, an ANOVA analysis of variance analysis was chosen to evaluate the results of the experiment; however, it was not possible due to the strong heterogeneity of the results. The analysis of residuals did not accomplish the assumptions about the residuals of the experiment. Therefore, it was decided to make a graphical exploratory analysis to obtain conclusions about the results.

The goal was to test the null hypothesis against the alternative hypothesis to discover the individual influence of the protocol factor in the response variables, and the interaction with the other factors, as well. Also, we wanted to measure the level of significance of such influence by the estimation of the difference in the mean of each response variable.

Table 1 shows the results obtained after running the experiment with all of its treatments.

Four conclusions could be obtained by analyzing the numerical results of the experiment. Moreover, a more accurate statistical analysis was executed in order to obtain a perspective from the results and to infer a more reliable set of conclusions.

Table 1.

Average results of the experiment, for all the treatments: traffic level: M-Medium, K-Ko9 #, delay in milliseconds, the percentage of packets lost in transmission, goodput in bits per second, and the percentage of remaining battery in the nodes.

	Cross-layer: abi et al.				1' ' ' () 2.1* . \$ + nslotted				1' ' ' () 2.1* . \$ %otted			
	+		%		+		%		+		%	
Number of nodes												
Traffic level	M	K	M	K	M	K	M	K	M	K	M	K
Delay ms	8.1%	8.44	8.4	(.++	+(	+1+	+13	+,%	1".(	14.(	+1.1+	1%4!
Packet loss rate B #	*,%	! ! +	*.1+	*,(	".1+	".4+	".4"	".4+	% .%	% %3+	% .(	% .3"
Goodput b/s	84.8"	8.43	!! (.4	!! .1+	4! .+%	4.1+	%4.(1	% %*+	*(.+!	*(.1	%! .4(	%! !
Remaining battery ratio B #	83.31	3".+8	((.+%	((.14	3.1"	3.(	3.8"	3.34	3+.1*	3(.%	3(.%	31.(

Source: The authors

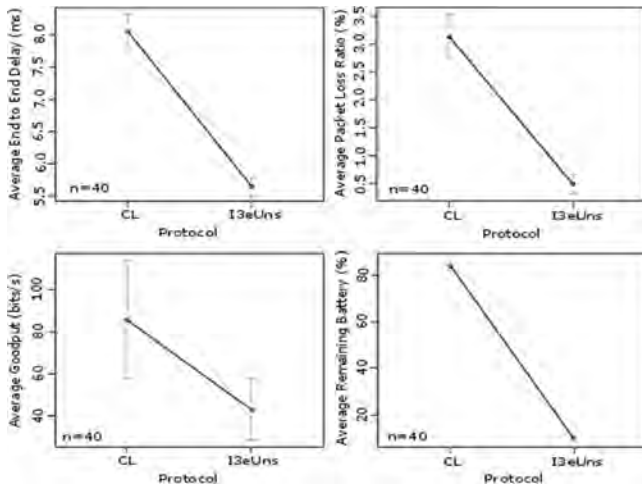


Figure 1. Average performance of the Eo' metrics in cross-layer <'.
(a) 4448"!. %4.4 unslotted
Source: The authors

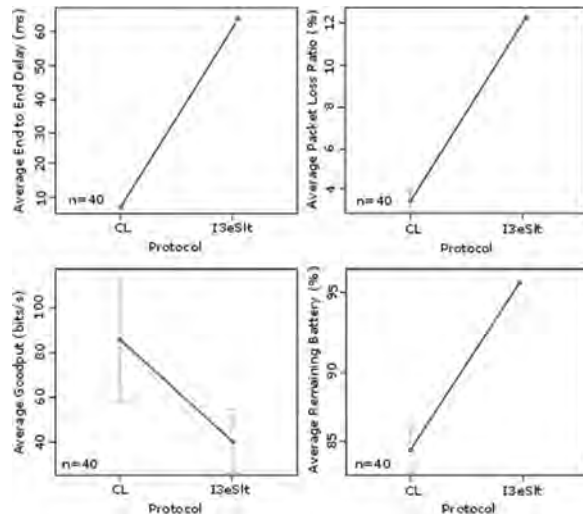


Figure 2. Average performance of the Eo' metrics in cross-layer <'.
(a) 4448"!. %4.4 slotted
Source: The authors

4.1. Cross-layer and IEEE802.15.4 unslotted

Figure 1 shows the results, in terms of means, for the response variables comparison between the cross-layer protocol and the unslotted mode of 4448"!. %4.4.

For average end to end delay and average packet loss rate response variables the null hypothesis is rejected, the statistics show the difference between the means obtained with both levels of protocol factor. Regarding the end to end delay metric, it is shown that 4448"!. %4.4 exhibits a slightly better performance. The difference in the means is close to 1.5 ms, which is not significant in 7.8 AN environments.

With regard to the Packet Loss Rate, the 4448"!. %4.4 unslotted outperforms the cross-layer protocol. This can be explained by the amount of lost packets that the later protocol exhibits when all nodes are adapting to the early states of the network.

Regarding throughput, the results match reality since the network using the cross-layer scheme broadcasts larger packets due to the loss of packets and end to end delay not far from those exhibited by 4448"!. %4.4 unslotted.

Regarding energy consumption, the results are totally conclusive, nodes using cross-layer protocol saved almost 3% of the battery in the entire simulation run, while when using 4448"!. %4.4 protocols only a 1% of the battery remained untouched.

4.2. Cross-layer and IEEE802.15.4 slotted

Figure 2 shows the results for the response variables comparison between the cross-layer protocol and the slotted mode of 4448"!. %4.4.

In this case, the only null hypothesis rejected is the one regarding the remaining battery load in the network. The difference between the response variables means for the rest of hypotheses is quite appreciable. For the end to end delay, Packet Loss Ratio and throughput metrics, a large difference is noticeable between the protocols. The best performance in those metrics is exhibited by the cross-layer protocol.

Moreover, regarding the battery consumption, a difference close to 15% in favor of 4448"!. %4.4 slotted can be observed. This result can be explained by longer inactive periods in 4448"!. %4.4 slotted and less slots in listening mode in 4448"!. %4.4 unslotted when compared with the cross-layer ones.

4.3. Transmission power

Another important issue that is considered in our experiments is the transmission power level. As mentioned in section 1, 7.8 AN nodes should not perform transmissions at high power levels, not only aiming to reduce energy consumption, but also trying to reduce the electromagnetic absorption rate in the body, which could result in health problems related to 7.8 AN use.

Figure 3 shows the transmission power levels for every node in 4 random chosen treatments of the experiments; i.e., 8, 3 correspond to 7.8 ANs formed by 2 + nodes and transmissions every 2 * seconds, and 4 + minutes respectively; while i.e., 5, 6 correspond to cases with 1 node.

It is evident that in networks using the cross-layer approach, nodes performed transmissions at lower power levels helping to reduce electromagnetic absorption. It can be observed that in 7.8 ANs with a greater density of nodes, the power level tends to reduce considerably among all nodes, even performing transmissions at the lowest power levels.

Such a result shows an extra benefit resulted from the use of the cross-layer protocol, as it prevents collateral damage and discomfort to 7.8 AN users.

*. Conclusions

The results show that regarding Eo' metrics, in most cases, the cross-layer protocol outperforms 4448"!. %4.4 in 7.8 AN scenarios. Regarding energy consumption, the cross-layer protocol is better than 4448"!. %4.4 unslotted but it cannot be said that it is worse than 4448"!. %4.4 slotted having in mind that the latter exhibited poor Eo' performance.

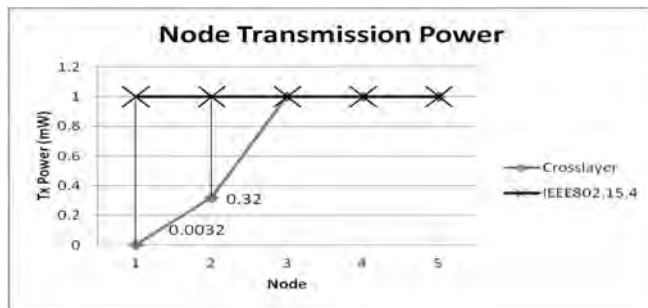


Figure 8. Performance of 7-8 AN nodes regarding transmission power levels net9 or A06+ nodes Wsendin0 \$acAets ever2 *'' seconds#
Source- The authors

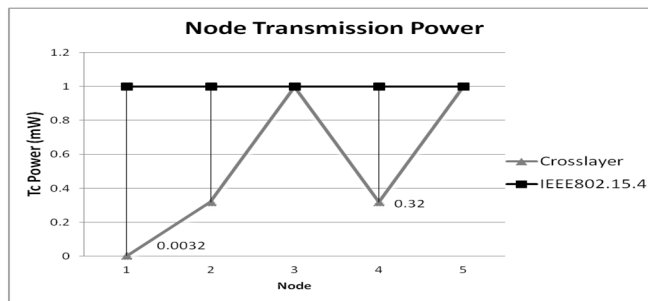


Figure 9. Performance of 7-8 AN nodes regarding transmission power levels net9 or A06+ nodes Wsendin0 \$acAets ever2 + minutes#
Source- The authors

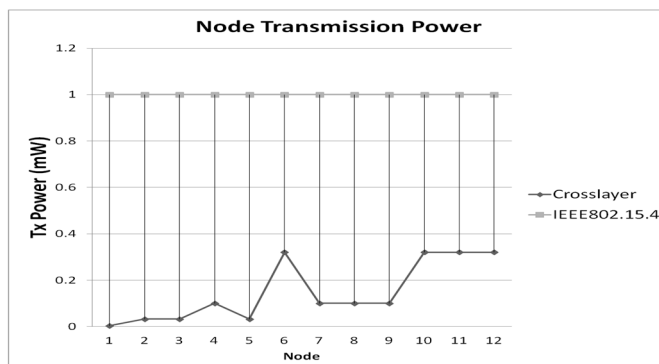


Figure 10. Performance of 7-8 AN nodes regarding Transmission Lo9 er levels net9 or A06% nodes Wsendin0 \$acAets ever2 *'' seconds#
Source- The authors

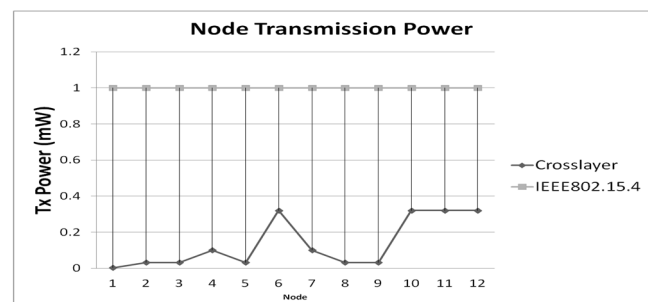


Figure 11. Performance of 7-8 AN nodes regarding Transmission Lo9 er levels net9 or A06% nodes Wsendin0 \$acAets ever2 + minutes#
Source- The authors

According to the premise of this comparison, the crosslayer protocol is more suitable for 7-8 AN than the standard 4448. Given the more accurate balance between energy consumption and energy metrics accomplishment exhibited by this communication scheme. In addition, the lower transmission power in the nodes using the crosslayer protocol helps to reduce the risks attributed to electromagnetic emissions in the human body.

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4 3drolo2ic and h3draulic simulations 5or use in macrodraina2e desi2ns 5or 2ull3 mana2ement and recover3

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Abstract

Runoff on susceptible terrains that is not associated with adequate drainage causes soil erosion, as alluvial fans. Alluvial fans and drainage continue to be major issues in reclamation projects since soil erosion can be reactivated after the application of recovery measures. This paper describes a low cost project framework for macrodrainage for a alluvial fan in Nardeno > : , <radial to provide support to alluvial fan management and recovery. It is used a simple methodology with the application of: erosion, information systems, and concentrated hydrologic and hydraulic models freely available software. The basin has steep slopes 8 to 15° and the water flow is mainly to the north-east, which contribute to exacerbate erosion problems. It is studied the effect of environmental conditions on different simulations to elaborate a drainage system project using the free software tools. Therefore, the findings of this paper can aid alluvial fan management and recovery for this and other areas with similar issues.

Keywords: Erosion; drainage system; MC2 method; Nardeno > : #

*imulaci3n hidrol3gica e hidr3ulica \$ara el dise1o de macrodrenaje \$ara la 2esti3n 3 recuperaci3n de c1rcavas

Resumen

Cursamiento superficial en terrenos susceptibles sin asociaci3n con el drenaje adecuado causa erosi3n del suelo. Las c1rcavas 3 el drenaje son importantes \$ara proyectos de recuperaci3n, 3a Aue la erosi3n \$uede ser reactivada desu3s de la aplicaci3n de t3cnicas de recuperaci3n. Describimos un proyecto de bajo costo \$ara macrodrenaje en Nardeno > : , < radial, \$orcionando soporte a la 2esti3n 3 recuperaci3n de c1rcavas. Utilizamos una metodol3gia con la aplicaci3n de: sistemas de informaci3n: eros3n, # 3 modelos hidrol3gicos 3 hidr3ulicos concentrados software libre. La cuenca ha \$resentado \$endientes elevadas 8 a 15° F, el flujo de agua es direccionado \$eferentemente al noroeste, contribuyendo al agravamiento de la erosi3n. Estudiamos el efecto de condiciones medioambientales en diferentes simulaciones \$ara un proyecto de sistema de drenaje usando las herramientas de software. Asimismo, los resultados de este art3culo \$ueden auxiliar la 2esti3n 3 recuperaci3n de c1rcavas \$ara esta 3 otras 1reas con \$problemas similares.

Palabras clave/ Erosi3n; sistema de drenaje; m3todo MC2; Nardeno > : #

1. Introduction

Grosive processes in agricultural areas result in runoff misdirection have been the focus of several studies (M The lack of an adequate drainage system, mainly on unsaved roads, is one of the main factors that cause water erosion in these areas (M According to LM erosion

associated with runoff on unsaved roads generates large environmental impacts, making the development of prevention and control strategies necessary. Given the embankments constructed within roads, it is an important role in sediment field and runoff concentrations (M

: alluvial fans are a common cause of water erosion and originate when some critical point among the environmental

How to cite: de Freitas *am\$ai0, G., *ilvestre Rodri2ues, G. de Almeida <ressiani, D. and > artins 7erreira, R.R., 4 3drolo2ic and h3draulic simulations 5or use in macrodraina2e desi2ns 5or 2ull3 mana2ement and recover3. DYNA, 84 (1), 4-14, 2015.

characteristics, such as sedimentation, runoff concentration, relief, soil types and the actual land use, is exceeded. It is still a challenge to determine which of the environmental factors are predominant in the enlargement or connections of gullies and how the gully reclamation could become convenient and reasonably feasible.

The results of research have indicated that direct control is crucial in minimizing the concentration of surface runoff and the formation and development of gullies. Direct control either with additional measures, such as constructing vegetated channels, planting vetiver grass or reclamation techniques with mulch applications, for example, proved to be efficient in reducing the amount of water flow and transported sediments.

As shown in Figure 1, there are many cases in which erosive processes are reactivated specifically due to the lack of proper water conveyance. In this context, free software, such as the ArcSWAT, can assist in the planning and preliminary design of restoration projects for degraded areas that involve drainage systems. Applied properly, combined correct land management practices and other specific actions, information generated by models could reduce soil losses considerably in the future.

The objective of this study was to develop a proposal for macrodrainage as an initial concept for a low-cost project through the use of the topographic tools discussed above, which were applied as part of a case study of the Cravo stream gully in Nardão. This area was chosen because there is a lack of studies regarding its surface water drainage and because Nardão is an example of how land use influences soil erosion in a susceptible environment, similar to other cities in Brazil.

2. Materials and methods

The Ussaré River (range River) in Minas Gerais (Brazil) and more specifically the city of Nardão are regions of high susceptibility to erosion, especially during the rainy season. It is possible to identify approximately 80 gullies in the city and its surroundings.



Figure 1. Cravo stream gully, near urban and rural areas of Nardão. Source: The authors.

The soils of the region are naturally susceptible to erosion mainly Cambisols that originated from the weathering of granite gneiss. Uses, such as mining, overgrazing and construction of unsaved roads with poor drainage conditions, among others, are still considered factors in the acceleration of these erosive processes and are major contributors to their reactivation.

The region of Nardão is located in the transition between the Atlantic Forest and the Cerrado. Natural resources of the municipal area and the use of the land for agriculture change the soil properties, including reductions in soil fertility, in the absence of proper management. The predominant soil types in Nardão are Red Yellowsols, Red Oxisols and Cambisols. The Cambisols are the most susceptible to erosion and are primarily associated with the intensive use of pasture areas.

According to the regional climate is characterized by an average annual rainfall ranging from 1,500 mm series from 1961 to 1990 to 1,800 mm series from 1991 to 2010. The winters are considered dry and the summers are rainy and humid (Cfa) according to Köppen classification. According to these authors, there is an average evapotranspiration of 800 mm with an annual average surplus of 800 mm and a deficiency of 1,000 mm during the period between January and April.

Among the erosion features listed in the city, we chose the Cravo stream gully because of its location between the rural and urban areas of Nardão and because its origin, similar to other gullies, is directly linked to improper drainage management and the consequent alterations in the soil dynamics associated with nearby roads. Moreover, landslides occurred within the gully in 1990 following reclamation activities that had been conducted along the gully, indicating that this dynamic is still active and causing instability within the gully.

Losses and flow direction maps were prepared at a scale of 1:10,000 in ArcGIS using the 7.1 ('QGIS') to 2D vector map. The 2D model was used for hydrologic simulation software for the study of surface runoff conditions. Decision support system for flood event analysis in ArcSWAT (version 2.2.5) from the support systems for Decisions in Water Resources Engineering and Environmental Engineering Laboratory (GAB) at the Nilton Lins Technical University of Umuarama (UNL) was used.

The Soil Conservation Service (SCS) method (United States Department of Agriculture) was used with the ArcSWAT software for calculating excess rain from the hydrograph considering 1-minute discretization intervals and varying the return period for 1, 2, 5, 10, and 25 years considering a first-order basin. This method allows for assigning the variables identified in the field using the variables of the 'Intensity Duration Frequency' (IDF) evaluation for 'aracena', a city near Nardão, and the Curve Number (CN) values.

The average CN of the basin was calculated based on information about the study area land use and soil type and considering the average soil moisture conditions. The IDF evaluation values, as well as the average CN, were obtained using the original data embedded in the software. A land use map of the Cravo stream gully contributing basin was prepared as part of the evaluation.

Finally, we evaluated the characteristics of the five flow conductors and the runoff activity among them using five Canal Channel software for dimensioning from the

Research : resources on Eater Resources at the Federal University of Rio de Janeiro.

The steeper slopes in the Tull area were used in this study considering minimal intervention in the terrain conditions. We tested channel construction hypotheses: circular and trapezoidal, as alternatives to the construction of channels with minimal use of heavy machinery to evaluate the surface runoff system and its velocity using alterations in the drainage characteristics, such as coverage to evaluate the roughness coefficient with or without vegetation, slope and the dimensions of the drainage, to simulate different runoff possibilities.

3. Results and discussion

The steepness classes identified for the Cravo stream catchment are shown in Figure 2. The slopes are predominant from 8 to 15% in the area. The 15% slope is the most frequent class that includes slopes ranging from 10 to 15%. Note that the area corresponding to the Cravo stream Tull has slopes between 10% and 15%.

It has been verified that the flow of surface runoff (Figure 2) is predominant directed towards the north-east. NE slope is the most frequent. Observations of the Cravo stream Tull indicate that its location is maintained in these two directions, i.e., the Tull is receiving the flow concentrations from the highest area

and road located in the basin north-east direction as well as the side road at the boundary. These runoff directions contribute to intense soil removal. As discussed by Lima (2013) conducted soil uses, e.g., roads compacted without a proper drainage system near the head of Tull's drainage area, exacerbate the problem because they intensify the flow concentrations that are natural convergences towards the Tull.

Considering that the terrain has favorable conditions for the concentration of flow, a theoretical study of the water surplus based on projected rains that have a specific probability of occurrence in the area was performed using A-C) software. Figure 4 presents the three main land uses obtained from field campaigns in 2010 and using ArcGIS, which were used to estimate the CN values from the values directly tabulated in the software and data used in the software for the A-C) method Table 1.

Thus, we obtained the maximum flow and runoff information based on hydrologic simulation performed in A-C). The return periods that were considered are commonly used for small-scale drainage projects to either consider other values for general evaluation and security Table 1.

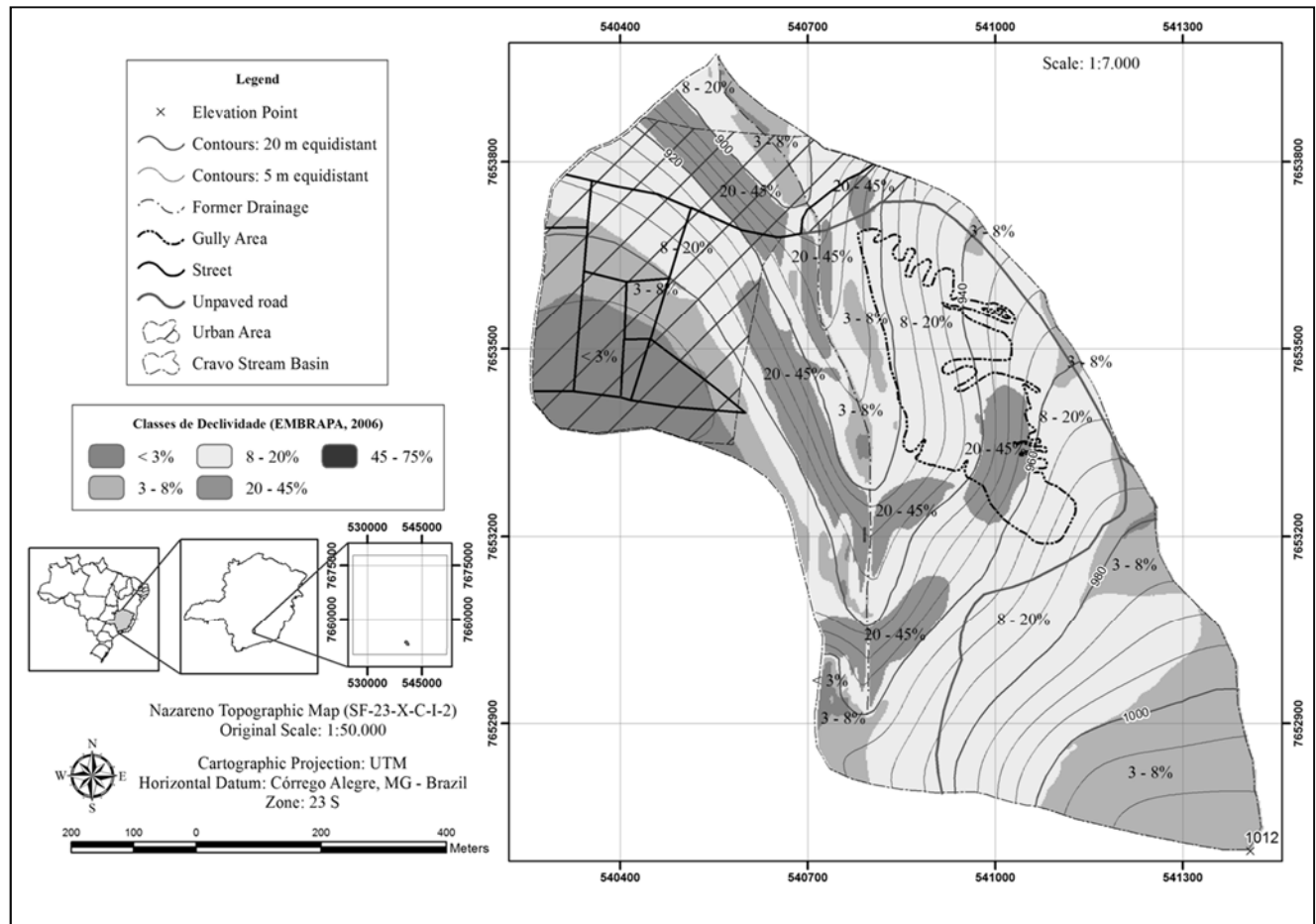


Figure 2. Slope classes map of Cravo stream catchment, Nazareno. Source: The authors.

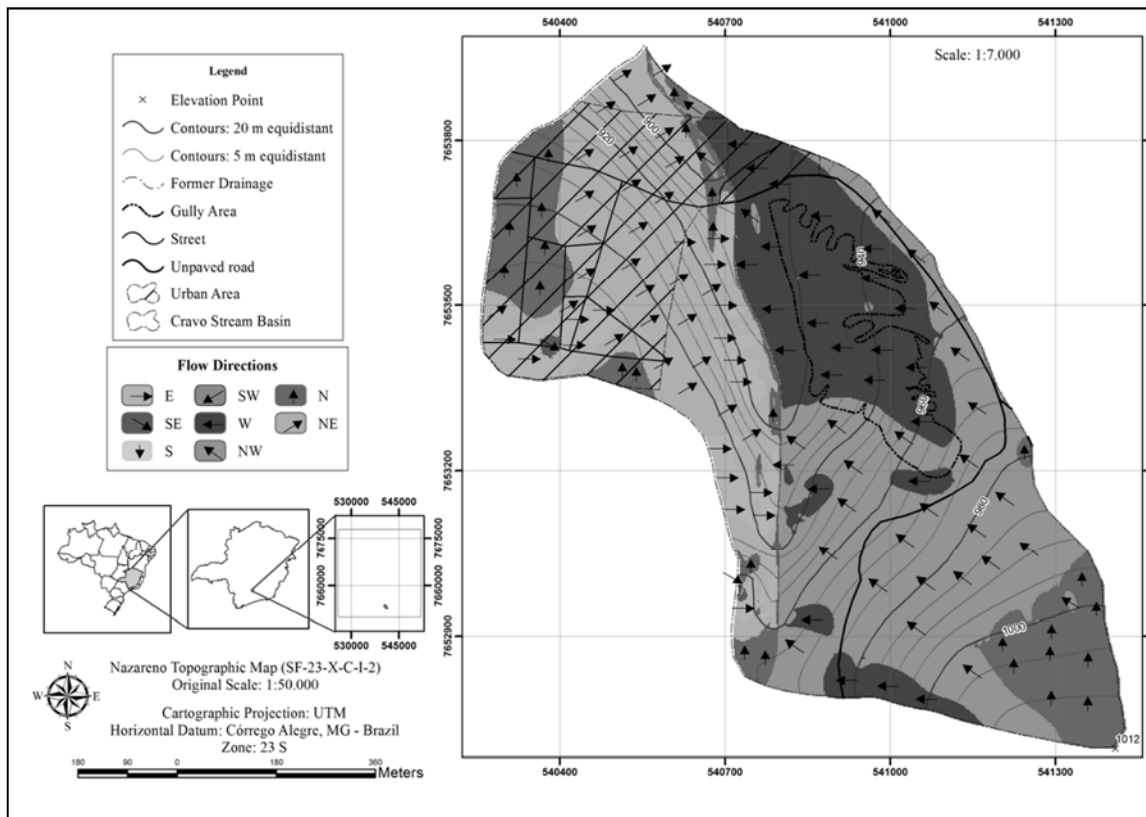


Figure 3. Flow direction map, Cravo Stream Basin, Nazareno.

Source: The authors.

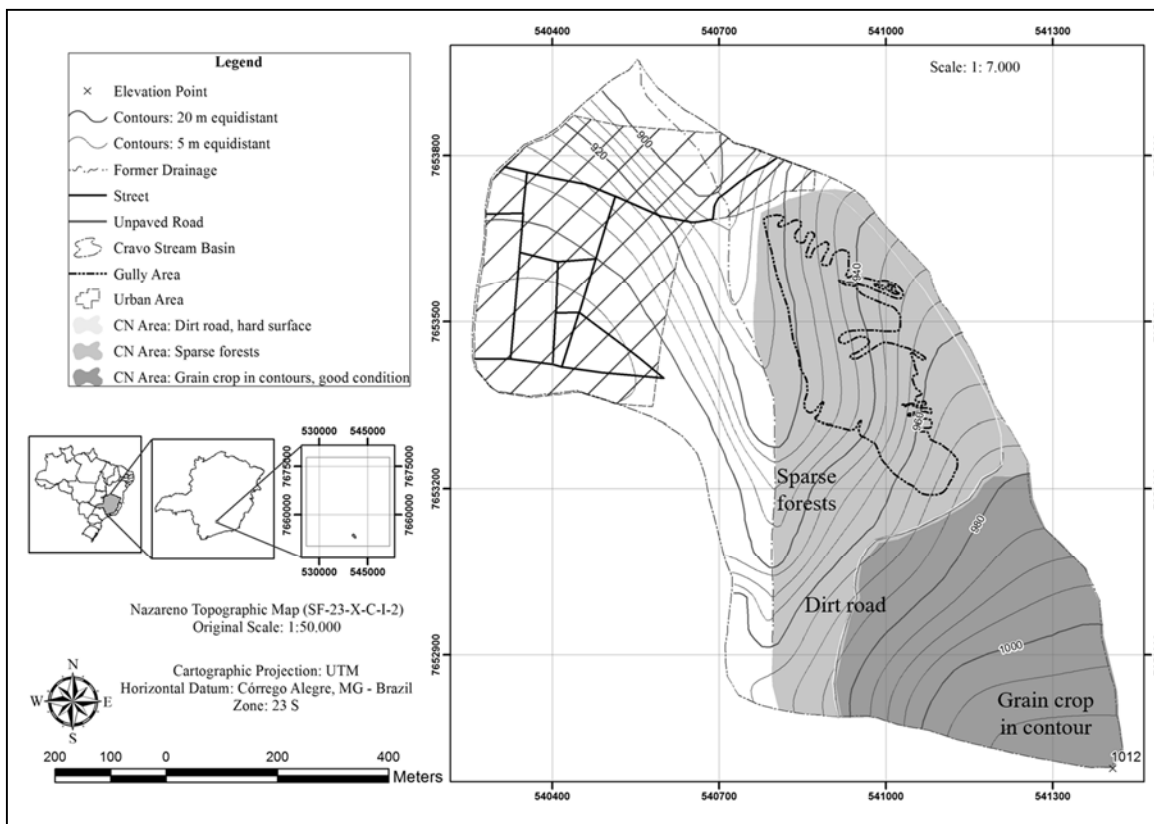


Figure 4. CN areas, Nazareno.

Source: The authors.

Table %

G\$timated \$arameters for h3drolo2ic simulation usin2 the *C* method in A<C).

Data – Concentration time		SCS Method		Intensity	
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Di\$ference in elevation m#	) 4.88&&	: rain cro\$ in contours	" . %8-	8!	
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*ource/ The Authors.

Table !

> alimum \$o@ rates and \$reci\$itation sur\$us for each return \$eriod considered ' A<C) Cravo *tream 2ull3 contributin2 basin, NaDareno' > : #

Return eriod	Ma(imum)low	Ma(imum) sur lus
"ears#	"m'.S#	"mm#
-	! .+ 4	%8."4
%	(.4-	!! .4!
%	(.88%	! - .%4
! "	4. ! " -	! + .%)
! -	4.4) -	! 8. +)

*ource/ The Authors.

These estimates indicate that a lar2e @ater load is mobili2ed to@ard the Cravo *tream 2ull3. E hen combined @ith the stee\$ slo\$es, this @ater load attains su\$icient velocit3 and stren2th to breaC u\$ the soil \$articles, @hich are alread3 under hi2h erodibilit3 conditions e\$pecial3 in areas @here the Cambisol is e1\$osed. This soil is easil3 trans\$orted because it does not have su\$icient cohesion to resist erosion and is characteri2ed b3 a hi2h de2ree o5 @eatherin2 @ith a \$redominance o5 Caolinite 1%4,% M ,t is em\$hasi2ed that the values \$ound @ith A<C) *C* method# @ere ori2inated from a\$ \$rolimations and have associated uncertainties. The \$arameters ma3 not re\$resent e1act values in situ and the h3drolo2ic \$ormulations have limitations. Nonetheless, it @ould be necessar3 to reduce @ater load contribution and @ater velocit3 so that the @ater could enter draina2e channels on the sides o5 the 2ull3 @ith less \$orce. A viable \$ro\$osal @ould be to ma2e use o5 the land area less suscep3ible to erosion and @ith lo@er in\$iltration rates to slo@3 absorb a considerable amount o5 @ater at the head o5 the Cravo *tream 2ull3 6 atosol\$ in the earl3 sta2es o5 runo\$.

Thus, the construction o5 a subsurface drain or an in\$iltration trench at the head o5 the 2ull3 is \$ro\$osed to reduce runo\$ and dam\$en its \$eaC in\$ut in the 2ull3 re2ion to minimi2e erosion 7i2. - #.

Table (summari2es the \$rimar3 cases evaluated in our stud3 based on the circular' t3\$e and tra\$e2oidal' t3\$e channel \$arameters considered for the \$ro2ect \$ro\$osal.

,n simulations @ith desi2n \$lo@s havin2 lo@er or hi2her

return times, it has been observed that a surface @ith a ver3 hi2h rou2hness coe\$icient @ould be necessar3 to maintain a non'turbulent \$lo@ in circular channels. The cases in our stud3 @ith rou2hness coe\$icient closest to reachin2 these hi2h values @ere Cases % (and 4 Table (#, ho@ever, the \$lo@rate o5 the @ater @ould 2reatl3 increase close to %m.s' % in each case, and maintainin2 a non'turbulent \$lo@ @ould onl3 be \$ossible b3 maintainin2 dense covera2e in the channels. U "M sho@ed that the > annin2 rou2hness coe\$icient can be increased @ith a dense cover, such as stra@, @hich @ould also reduce the runo\$ velocit3.

All simulations @ith circular channels @ere \$er\$ormed @ith an avera2e stee\$ness o5 the stud3 area. As such, the channel con\$ \$uration alteration in conjunction @ith slo\$e chan2es @as studied in addition to veri\$yin2 the relationshi\$ bet@een the channel rou2hness and \$lo@rate Table (#. There is a relationshi\$ bet@een the channel rou2hness, the slo\$e and the runo\$ velocit3. As the channel rou2hness increases coverin2#, there are more \$ossibilities to build a channel in a more inclined location @hile maintainin2 the same \$lo@ velocit3.

7or the Cravo *tream 2ull3, for e1am\$le, this alternative @ould avoid an e1cess o5 soil movement and landsca\$e alteration, and this measure @ould be com\$atible @ith that needed for 2ull3 recover3.

7i2. - sho@s the desi2n o5 an initial draina2e s3stem \$ro2ect for the Cravo *tream 2ull3, in NaDareno. The main \$ocal \$oints o5 the desi2n are the collection and in\$iltration o5 @ater that is directed to the north, thus reducin2 the @ater su\$li3 that @ould be directed to a channel circular or tra\$e2oidal# @hich @ould be oriented in the area in a southeast' north@est direction. To avoid the hi2her e1\$enses associated @ith slo\$e ad\$ustment for the construction o5 the channel, it should be lined roc\$ ve2etation, or combination o5 both# to establish an a\$ \$ro\$riate rou2hness coe\$icient, decreasin2 the velocit3 and ener23 @ith @hich the @ater encounters the soil \$articles, thereb3 reducin2 the removal and trans\$ort o5 the Cambisol more suscep3ible to erosion 2round#. This t3\$e o5 initial \$ro2ect desi2n is necessar3 because it hel\$ in reducin2 the costs and e\$ \$ort associated @ith earth@orC.

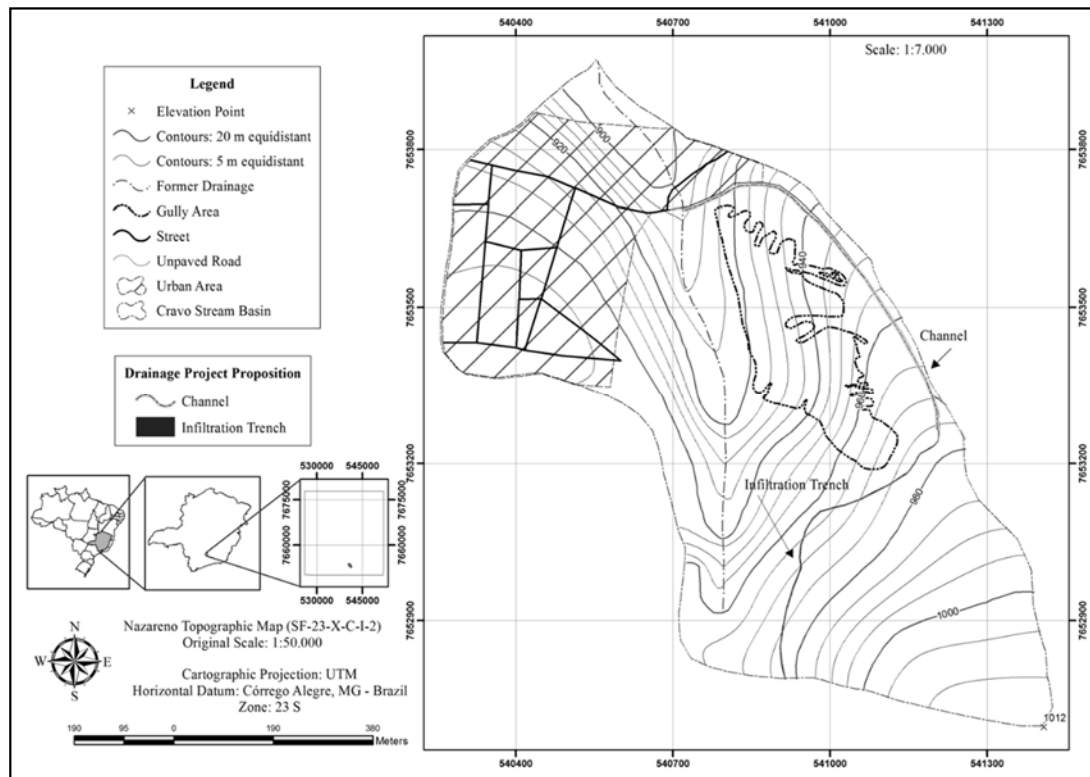


Figure 2. Drainage project design for the Cravo Stream in Nazareno. Source: The Authors

Table 1. Studies with parameter variations in the Channel section.

Channel design				
Circular stud%	Design parameters	Parameter found	Results	
	Discharge (m³.s⁻¹)	Mannings roughness coefficient	Flow regime	Seed (m.s⁻¹)
1%	1.5	0.015	Subcritical	0.4
1.5%	1.5	0.015	Subcritical	0.4
2%	1.5	0.015	Subcritical	0.4
4%	1.5	0.015	Subcritical	0.4
Mannings roughness coefficient				
		Depth (m)	Diameter (m)	
		0.8	0.8	Subcritical
Results				
		Slope (m.m⁻¹)	Flow regime	Seed (m.s⁻¹)
1%	1.5	0.015	Subcritical	0.4
1.5%	1.5	0.015	Subcritical	0.4
Mannings roughness coefficient				
		Discharge (m³.s⁻¹)	Flow regime	Seed (m.s⁻¹)
1%	1.5	0.015	Subcritical	0.4
1.5%	1.5	0.015	Subcritical	0.4
Mannings roughness coefficient				
		Discharge (m³.s⁻¹)	Flow regime	Seed (m.s⁻¹)
1%	1.5	0.015	Subcritical	0.4
1.5%	1.5	0.015	Subcritical	0.4

a/ Depth (m); Slope (m.m⁻¹); Diameter (m)

b/ Depth (m); Slope (m.m⁻¹); Diameter (m)

c/ Depth (m); Slope (m.m⁻¹); Diameter (m)

d/ Depth (m); Slope (m.m⁻¹); Diameter (m)

e/ Slope (m.m⁻¹); Slope (m.m⁻¹); Depth (m)

f/ Depth (m); Mannings roughness coefficient (s.m⁻¹); Slope (m.m⁻¹); Channel length (m); Slope (m.m⁻¹); Seed (m.s⁻¹)

g/ Depth (m); Slope (m.m⁻¹); Slope (m.m⁻¹); Channel length (m); Slope (m.m⁻¹); Seed (m.s⁻¹)

h/ Depth (m); Mannings roughness coefficient (s.m⁻¹); Slope (m.m⁻¹); Channel length (m); Slope (m.m⁻¹); Seed (m.s⁻¹)

i/ Depth (m); Mannings roughness coefficient (s.m⁻¹); Slope (m.m⁻¹); Channel length (m); Slope (m.m⁻¹); Seed (m.s⁻¹)

j/ Depth (m); Mannings roughness coefficient (s.m⁻¹); Slope (m.m⁻¹); Channel length (m); Slope (m.m⁻¹); Seed (m.s⁻¹)

Source: The Authors.

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Evaluating supervised learning approaches for spatial-domain multi-focus image fusion

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Abstract

Image fusion is the generation of an image f that combines the most relevant information from a set of images of the same scene, acquired with different cameras or camera settings. Multi-Focus Image Fusion (MFIF) aims to generate an image f_e with extended depth-of-field from a set of images taken at different focal distances or focal planes, and it proposes a solution to the typical limited depth-of-field problem in an optical system configuration. A broad variety of works presented in the literature address this problem. The primary approaches found there are domain transformations and block-of-pixels analysis. In this work, we evaluate different systems of supervised machine learning applied to MFIF, including k-nearest neighbors, linear discriminant analysis, neural networks, and support vector machines. We started from two images at different focal distances and divided them into rectangular regions. The main objective of the machine-learning-based classification system is to choose the parts of both images that must be in the fused image in order to obtain a completely focused image. For focus quantification, we used the most popular metrics proposed in the literature, such as: Laplacian energy, sum-modified Laplacian, and gradient energy, among others. The evaluation of the proposed method considered classifier testing and fusion quality metrics commonly used in research, such as visual information fidelity and mutual information feature. Our results strongly suggest that the automatic classification concept satisfactorily addresses the MFIF problem.

Keywords: Multi-focus image fusion; image processing; supervised learning; machine learning.

Evaluando aproximaciones basadas en aprendizaje supervisado para la fusión en el dominio espacial de imágenes multi-foco

Resumen

La fusión de imágenes genera una imagen f que combina las características más relevantes de un conjunto de imágenes de la misma escena adquiridas con diferentes cámaras o configuraciones. La Fusión de Imágenes Multifoco (MFIF) parte de un conjunto de imágenes con diferente distancia focal para generar una imagen f_e con una profundidad de campo extendida. Lo que constituye una solución al problema de la profundidad de campo limitada en la configuración de un sistema óptico. La literatura muestra una amplia variedad de trabajos que abordan este problema. Las transformaciones de dominios y el análisis de bloques de píxeles son la base de los principales enfoques propuestos. En este trabajo se presenta una evaluación de diferentes sistemas de aprendizaje supervisado aplicados a MFIF, incluyendo k-vecinos más cercanos, análisis discriminante lineal, redes neuronales y máquinas de soporte vectorial. El método inicia con dos imágenes de la misma escena, pero con diferentes distancias focales que se dividen en regiones rectangulares. El objetivo principal del sistema de clasificación, que está basado en aprendizaje de máquina, es elegir las partes de ambas imágenes que deben estar en la imagen fusionada para obtener una imagen completamente enfocada. Para la cuantificación del enfoque se utilizaron las métricas más populares propuestas en la literatura como: la Energía Laplaciana, el Laplaciano Modificado por Suma y el Gradiente de Energía, entre otras. La evaluación del método propuesto incluye la fase de prueba de los clasificadores y las métricas de calidad de fusión utilizadas comúnmente en la investigación, tales como la fidelidad de la información visual y la característica de información mutua. Los resultados muestran que el concepto de clasificación automática puede abordar satisfactoriamente el problema MFIF.

Palabras clave: Fusión de imágenes multifoco; procesamiento de imágenes; aprendizaje supervisado; aprendizaje de máquina.

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1. Introduction

Traditional optical systems are limited by focus range, which means that not all objects in a scene appear clearly defined [1], so only the objects within the field of depth of the camera are focused and are perceived clearly, while the rest of the scene is blurred [2]. Thus, to generate an image with all objects adequately focused, the academic community used the idea of forming a synthetic image by fusing a set of images of the same scene. This is called Multi-Focus Image Fusion (MFIF). The MFIF process consists of merging multiple images with different focal planes to generate an image in which all objects appear sharp [3] without the introduction of any artifacts.

The application of MFIF is widespread and used to solve problems related to three-dimensional reconstruction [2,4], mobile image processing, microscopic imaging [5], and computer vision [6], among others.

To generate an extended-focus image from a sequence of partially focused images of the same scene, digital image descriptors called focus measures [7] are used in different approaches.

MFIF is generally divided into two major types of methods [1,8-9]:

- spatial-domain image fusion methods;
- frequency-domain image fusion methods.

The spatial-domain methods use measurable characteristics of spatial information of image pixels. They estimate these measures pixel by pixel or by using pixel sets [10,11]. The principal advantages of these methods are that they are easy to implement and require low computational complexity. However, they do require rich texture information in an image to generate good results and are usually weak in smooth image regions. Furthermore, grouping of pixels presents difficulties related to the correct determination of group size for quality maximization and to the presence of artifacts generated on border blocks [3].

Various approaches within the special-domain methods of MFIF have been applied. For example, K.L. Hua et al. [11] used random walks on graphs created from several feature sets of focus measures and color consistency to model local and global characteristics. This approach estimated the measures in each pixel locally for each input image and used them to maximize the global focus score and color consistency. On the other hand, a method based on sparse feature matrix decomposition using morphological filtering to extract salient features of original input images, was proposed in [12]. They used a pixel-wise methodology to fuse each sparse feature matrix estimation based on morphological filtering to generate the fused image.

Some works use hierarchical structures called QuadTree for recursively partitioning the pixel space of the image and decompose the input images into blocks of variable size [13,14]. Using a focus measure based on the sum-modified-Laplacian (SML), the method detects the focused regions. So, the resulting image is generated using the focused regions of input images. The main problem with partitioned methods is determination of the correct block size. Avoiding defocused regions in large regions or small blocks with low-contrast

variance is the main challenge of QuadTree [14]. Similarly, the accuracy of the partitioning depends on searching deep in the tree, which has a direct impact on the computational cost. Other graph-based works are found in [15,16].

Another approach for dealing with the selection of focused regions in images is the segmentation approach. S. Li et al. [17] proposed a method that uses morphological filtering for rough segmentation of the images based on an initially estimated focus map. The method then uses the *image matting* technique to refine the segmentation results and a merging process to generate the final image. Another segmentation approach was proposed by M. Nejati et al. [18], based on a training and a testing phase. The training phase constructs a dictionary using focus information maps from local patches of source images. Each pixel from each input image is classified as in focus or not in focus. The final image results from pixel fusion according to a decision map that indicates which source image must be used to obtain the pixel intensity value. Overall, although the segmentation/optimization-based methods applied to the problem of image fusion generate adequate results, they involve a high computational cost.

Frequency-domain image fusion methods transform input images into a frequency domain representation where they are combined. One approach within this category is based on multi-scale decomposition. This is the most commonly reported approach to MFIF. For example, a shift and rotation invariant pyramid representation called Steerable Pyramid was applied by Z. Lin et al. [22]. Other frequency representations reported are Discrete Wavelet Transform [7,23] and Robust Principal Component Analysis [6]. Frequency-domain image fusion methods can be applied to multi-focus and multi-modal images with acceptable behavior. However, they add some noise level and cannot guarantee fidelity of the input image in the final image.

The MFIF problem can be stated as a classification problem where the classifier must decide in which source image the pixel or region has a high focus measure. J. Saeedi and K. Faez proposed a wavelet-based MFIF method which used a two-class Fisher classifier to group the regions into focused and defocused ones [19]. To reduce the number of misclassified regions due to uncertainty, they included a fuzzy logic algorithm. On the other hand, some works reported the use of other types of classifiers, such as neural networks, to tackle the MFIF problem [20,21].

The aim of this study is to compare various classification approaches to the MFIF problem. We selected four popular focus measures and proposed a new one based on morphological features; then we used these as classifier inputs.

This paper is organized as follows. In Section 2, we present the methodology used in this study, including the data and vector feature selection, training, and fusion stages. Section 3 presents the results obtained and comparisons. Finally, Section 4 concludes with a summary and future works.

2. Methodology

We establish the MFIF as a classification problem where the aim is to process a pair of input images, labeling their

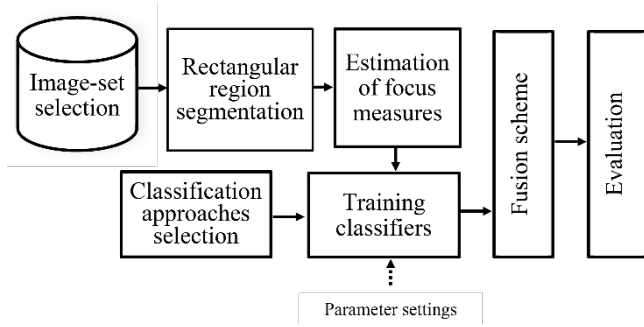


Figure 1. Blocks diagram of used methodology.
Source: The authors.

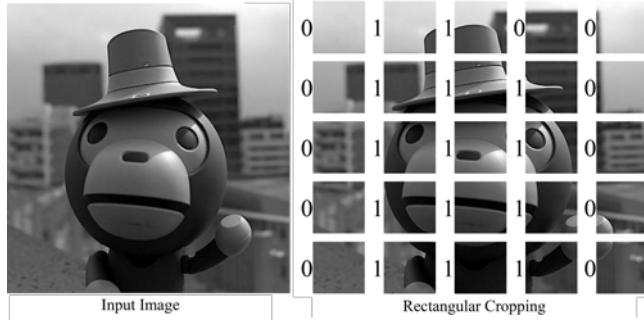


Figure 2. The scheme used to form the subset of images.
Source: The authors.

regions as focused and defocused, in order to build up a final image that merges the focused regions. The methodology begins by selecting the image set used for the training and testing stages. After the image set was defined, we selected focus measures reported in the literature and machine-learning-based classifiers. The training process and the image fusion were the next methodological stages. Finally, we carried out an evaluation step to compare the behaviors of the selected classifiers. Figure 1 shows a block diagram of the methodology used.

2.1. Image-set selection and rectangular segmentation

Our initial set of images consisted of 30 pairs of multifocus images taken from public datasets [18,24] and a set of images of our own acquired in the laboratory. Every pair consisted of two images: a near-focused one and a far-focused one. Then, using rectangular cropping, a subset of 830 images was constructed and associated with a binary tag (*focused:1, defocused:0*) by human judgment. Figure 2 illustrates this process.

2.2. Focus measures and feature vector formation

In the MFIF context, a focus image operator is a local metric that quantifies the quality of focus in an image region. Ideally, when the region is perfectly focused, these operators must generate a maximum value [25] that decreases in a similar way when the image becomes blurred. Many focus metrics have been proposed by the scientific community. A typical focus metric should satisfy the following requirements [7]:

- independence of image content
- monotonicity of blur
- unimodality (only one maximum value)
- value variation according to degree of blurring
- minimal computation complexity
- robustness to noise

We selected four focus measures frequently used in reported works [7] and proposed a new focus measure based on morphological features.

Let us consider $f(x, y)$, the intensity level of a pixel (x, y) . The selected focus measures are defined below:

2.2.1. Energy of Laplacian

The Energy of Laplacian (EOL) of an image f is computed as:

$$EOL = \sum_x \sum_y (f_{xx} + f_{yy})^2 \quad (1)$$

Where

$$\begin{aligned} f_{xx} + f_{yy} = & -f(x-1, y-1) - 4f(x-1, y) \\ & - f(x-1, y+1) \\ & - 4f(x, y-1) + 20f(x, y) \\ & - 4f(x, y+1) \\ & - f(x+1, y-1) \\ & - 4f(x+1, y) \\ & - f(x+1, y+1) \end{aligned} \quad (2)$$

2.2.2. Sum-modified Laplacian

The modified Laplacian is a proposal to avoid the cancellation trend of the second derivate in the EOL basic definition [25]. So, the SML is defined by equations (3) and (4):

$$\begin{aligned} \nabla^2_{ML} f(x, y) = & |2f(x, y) - f(x - \beta, y) \\ & - f(x + \beta, y)| \\ & + |2f(x, y) - f(x, y - \beta) \\ & - f(x, y + \beta)| \end{aligned} \quad (3)$$

where β is a spacing parameter addressing the accommodation of texture variation in the image and set to $\beta = 1$.

$$SML = \sum_{i=x-N}^{i=x+N} \sum_{j=y-N}^{j=y+N} \nabla^2_{ML} f(i, j) \text{ for } \nabla^2_{ML} f(i, j) \geq T \quad (4)$$

where T is a discrimination threshold value and N is the window size.

2.2.3. Energy of image gradient

This operator is based on the concept of determining the local high-frequency variations. The Energy of Gradient (EOG) can be computed as:

$$EOG = \sum_x \sum_y (f_x^2 + f_y^2) \quad (5)$$

Where

$$f_x = f(x+1, y) - f(x, y) \quad (6)$$

$$f_y = f(x, y+1) - f(x, y) \quad (7)$$

2.2.4. Spatial Frequency

Spatial frequency (*SF*) is a modification of the energy of image gradient operator. It is defined as:

$$SF = \sqrt{RF^2 + CF^2} \quad (8)$$

where *RF* and *CF* are the row and column frequency respectively.

$$RF = \sqrt{\frac{1}{M \times N} \sum_{x=1}^M \sum_{y=2}^N [f(x, y) - f(x, y-1)]^2} \quad (9)$$

$$CF = \sqrt{\frac{1}{M \times N} \sum_{x=2}^M \sum_{y=1}^N [f(x, y) - f(x-1, y)]^2} \quad (10)$$

2.2.5. Energy of morphological features

We propose a new focus measure based on the metric defined in [17] and the concept of the energy of the image. We named this focus measure as the *Energy of Morphological Features (EMF)*. We used a combination of bottom-hat and top-hat operations to first extract salient local features and then calculate the sum of maximum values for a window.

$$EMF(W_{M \times N}^I) = \frac{1}{M \times N} \sum_{i=1}^N \sum_{j=1}^M \max(T_{i,j}, B_{i,j})^2 \quad (11)$$

Let *T* and *B* be top-hat and bottom-hat morphological operations, respectively, centered at the pixel with coordinates (*i,j*). We describe the *EMF* of a local window *W* of an input image *I*. Finally, we build up a feature vector $\vec{\gamma}$ composed of the ratio of each focus measure of input images *A* and *B*. Figure 3 shows the structure of the feature vector.

$\frac{Eol_A}{Eol_B}$	$\frac{Sml_A}{Sml_B}$	$\frac{Eog_A}{Eog_B}$	$\frac{Sf_A}{Sf_B}$	$\frac{Emf_A}{Emf_B}$
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Figure 3. Vector feature structure.
Source: The authors.

2.3. Classifier selection

Because the MFIF has been established as a classification problem, we selected the most representative classification approaches in the literature: Linear Discriminant Analysis (LDA) [26], naïve Bayes [27-29], k-nearest neighbors (k-NN) [30], random forest, multilayer perceptron (MLP) [31], and support vector machine (SVM) [32]. The two classes for region classification were focused and defocused regions, represented as a binary tag.

2.4. Training procedure

We created a binary classification dataset using the previously created subset of images with binary tags and the feature vector formation scheme described in Section 2.2.

With this dataset, each binary classifier was trained and tested using cross-validation. Then, the best score classifier of each classification technique was saved for the posterior fusion scheme.

For this purpose, the Python with Scikit-learn [33] and PyBrain [34] libraries were used to configure, train, and test different classifiers.

2.5. Fusion scheme

The fusion scheme proposed in this work is composed of two main stages. In the first stage, a binary mask is generated with information about which regions of both images have high focus (Fig. 4). In the second stage, the fused image is obtained using input images *A* and *B* and the binary mask obtained in the first stage (Fig. 5).

2.5.1. Stage 1 – Binary mask generation

The first stage begins by moving a rectangular window over a pair of input images and iteratively describing each window as a feature vector. Then, the ratio $\vec{\gamma}$ of these two vectors (Fig. 3) is used as an input for a trained classifier which returns a binary label (*focused:1*, *defocused:0*) for the highest focus in image *A* or *B* respectively. This binary label is used to build a binary mask *Z* of resolution equal to the moving window size. This mask contains information about the highly focused regions in both input images.

$$Z(x_0:x_1, y_0:y_1) = C(\vec{\gamma}_{x_0:x_1, y_0:y_1}) \quad (12)$$

Equation (21) describes stage 1, where *Z* is the binary mask matrix, the range (*x*₀:*x*₁, *y*₀:*y*₁) is the image portion of the sliding window, *C* is the binary classifier, and $\vec{\gamma}_{x_0:x_1, y_0:y_1}$ is the ratio of the feature vector of input images *A* and *B* for the sliding window in the range (*x*₀:*x*₁, *y*₀:*y*₁).

A scheme of the generation of the binary mask *Z* in stage 1 is shown in Figure 4.

2.5.2. Stage 2 – Image fusion

It is possible to generate a fused image using the binary mask obtained in stage 1, but because of the rectangular

nature of the moving window, a high number of artifacts can be generated in regions containing borders of objects (see the rough behavior of borders and holes in Z in Figure 4). An improved result can be obtained by smoothing the binary mask.

This stage begins by applying the morphological operation *close* to group individual pixels and fill holes in the binary mask. Then a low-pass filter (*median blur*) is applied to delete random noise and smooth the borders of the binary mask. Both operations used rectangular kernels of the same size. Finally, using the smoothed binary mask Z' , input images A and B are cropped to generate the fused image F . This process is illustrated in Figure 5.

$$F = A \times Z'_A + B \times Z'_B \quad (13)$$

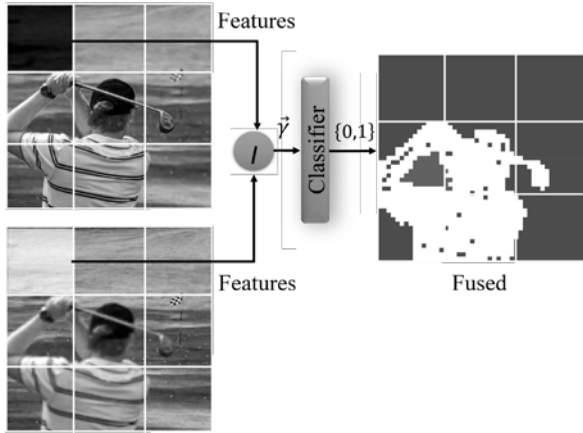


Figure 4. Scheme of the generation of binary mask Z in stage 1.
Source: The authors.

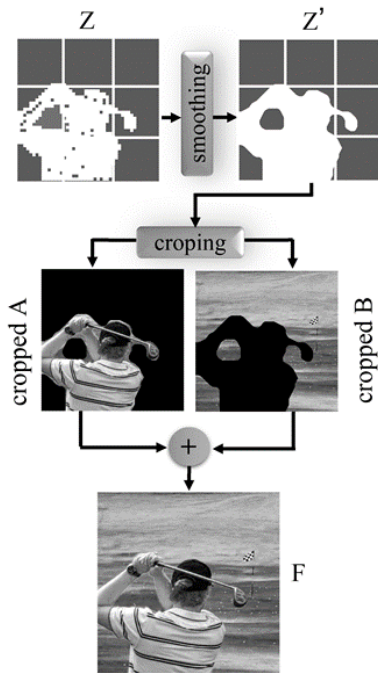


Figure 5. Scheme of stage 2 for the generation of the fused image F .
Source: The authors.

Equation (22) describes stage 2, where F is the image fused using the proposed scheme, A and B are the input images, Z'_A and Z'_B are the pixels of the smoothed mask belonging to images A and B respectively, and $\times$ is an element-wise multiplication of two matrices.

2.6. Fusion quality measure

The fusion quality metric reflects the quality of visual information of a fused image obtained from a set of input images [35]. Evaluation of image fusion algorithms has become an important issue due to the different complexity characteristics used by several proposed approaches. Typically, the way in which the quality of the fused images is measured is by the mean of experts who score them. This approach does not offer a general way to evaluate approaches automatically and implies a costly effort. However, for objective evaluation of fusion results, we use three fusion-quality metrics including Visual Information Fidelity for Fusion (VIFF) [36], Petrovic's metric based on edge information ($Q^{AB/F}$) [35], and Feature Mutual Information (FMI) [37].

2.6.1. Visual information fidelity for fusion

VIFF is founded on the Visual Information Fidelity (VIF) quality metric based on Natural Scene Statistics theory, which measures the visual information by computing mutual information between different models estimated from images. These models are in the wavelet domain and include Gaussian Scale Mixture, the distortion model, and the Human Visual System.

The common procedure for VIF estimation is to divide the images into k sub-bands, each of which is divided in turn into b blocks. The mutual information between the different models is estimated and VIF can be stated as:

$$VIF(I_r, I_d) = \frac{\sum_k \sum_b \left(1 + \frac{g_{k,b}^2 \cdot (\sigma_{k,b}^r)^2}{((\sigma_{k,b}^d)^2 - g_{k,b}^2 \cdot (\sigma_{k,b}^r)^2 + \sigma_N^2)} \right)}{\sum_k \sum_b \left(1 + \frac{(\sigma_{k,b}^r)^2}{\sigma_N^2} \right)} \quad (14)$$

2.6.2. Edge-based fusion performance

This metric is based on the idea of quantifying the important information preserved in the fused image. The important information is associated with edge information, and therefore the metric measures the amount of edge information transferred from input images to the fused image, using a Sobel operator to get the relative edge strength and orientation between the input and fused images [35].

Let A be an input image and let the pixel $A(i, j)$ have an edge strength $g_A(i, j)$ and orientation $\alpha_A(i, j)$ defined as:

$$g_A(i, j) = \sqrt{S_A^x(i, j)^2 + S_A^y(i, j)^2} \quad (15)$$

$$\alpha_A(i, j) = \tan^{-1} \left(\frac{S_A^x(i, j)}{S_A^y(i, j)} \right) \quad (16)$$

where $S_A^x(i, j)$ and $S_A^y(i, j)$ are the result of applying a horizontal and vertical Sobel template centered on $A(i, j)$. The relative edge strength (G^{AF}) and orientation (Δ^{AF}) of the image A with respect to a fused image are defined as:

$$G^{AF}(i, j) = \begin{cases} \frac{g_F(i, j)}{g_A(i, j)}, & g_A(i, j) > g_F(i, j) \\ \frac{g_A(i, j)}{g_F(i, j)}, & \text{Otherwise} \end{cases} \quad (17)$$

$$\Delta^{AF}(i, j) = 1 - \frac{|\alpha_A(i, j) - \alpha_F(i, j)|}{\frac{\pi}{2}} \quad (18)$$

The edge strength and orientation preservation values can be derived by:

$$Q_g^{AF}(i, j) = \frac{\Gamma_g}{1 + e^{k_g(G^{AF}(i, j) - \sigma_g)}} \quad (19)$$

$$Q_\alpha^{AF}(i, j) = \frac{\Gamma_\alpha}{1 + e^{k_\alpha(\Delta^{AF}(i, j) - \sigma_\alpha)}} \quad (20)$$

where the constants Γ_g , k_g , σ_g , Γ_α , k_α , and σ_α determine the shape of sigmoid functions used to form the edge strength and orientation preservation value [35].

The edge preservation value is defined as:

$$Q^{AF}(i, j) = Q_g^{AF}(i, j) Q_\alpha^{AF}(i, j) \quad (21)$$

Finally, for input images A and B, the final weighted performance measure $Q^{AB/F}$ with respect to the fused image F is estimated as:

$$Q^{AB/F} = \frac{\sum_{n=1}^N \sum_{m=1}^M [Q^{AF}(i, j) w^A(i, j) + Q^{BF}(i, j) w^B(i, j)]}{\sum_{n=1}^N \sum_{m=1}^M (w^A(i, j) + w^B(i, j))} \quad (22)$$

2.6.3. Feature mutual information

Mutual Information (MI) is derived from information theory and quantifies the amount of information obtained about one variable from another variable. Thus, FMI quantifies the amount of image features transferred from the source images into the fused image. Gradient maps represent the images' features because they contain information about edges, directions, texture, contrast, and pixel neighborhoods [37]. Like classic approaches used to estimate MI, FMI estimation is based on the calculation of the joint probability distribution functions. Assuming the intensity pixels of the fused image $F(x, y)$ and input images $A(z, w)$ and $B(z, w)$, the methods use the normalized values of gradient magnitude image features, like marginal distributions, and therefore the

amount of feature information in the fused image F from input images A and B is given by [37]:

$$I_{FA} = \sum_{f,a} P_{FA}(x, y, z, w) \log_2 \frac{p_{FA}(x, y, z, w)}{p_F(x, y) \cdot p_A(z, w)} \quad (23)$$

$$I_{FB} = \sum_{f,a} P_{FB}(x, y, z, w) \log_2 \frac{p_{FB}(x, y, z, w)}{p_F(x, y) \cdot p_B(z, w)} \quad (24)$$

where P_{FA} and P_{FB} are the joint distribution between the fused image and each input image. p_F , p_A , and p_B are the marginal distributions. The FMI is defined as:

$$FMI_F^{AB} = I_{FA} + I_{FB} \quad (25)$$

Based on [37-39], the normalized FMI can be obtained as:

$$FMI_F^{AB} = \frac{I_{FA}}{H_F + H_A} + \frac{I_{FB}}{H_F + H_B} \quad (26)$$

where H_F , H_A , and H_B are the histogram-based entropies of the images A, B, and F.

3. Experiments and results

In this section, we present detailed experimental settings used to evaluate the performance of the classification approach for MFIF from two perspectives: classifier performance and fusion quality. The first evaluates the learning ability of a classifier to decide whether or not an image is focused. The second measures the fusion result generated by a classifier of the information contained in the input images. Finally, we discuss the results exhibited.

3.1. Classifier performance

We selected five binary classifiers and trained them with the parameters shown in Table 1 and a dataset of 830 images labeled as binary for focused or defocused cases.

Training parameters were obtained experimentally, selecting the set of parameters that allowed us to obtain the best results.

Table 1.
Parameters used for training binary classifiers

Binary Classifier	Parameters	Technology
LDA	N/A	Scikit-learn
k-NN	$k = 3$	Scikit-learn
Gaussian Naïve Bayes	N/A	Scikit-learn
RBF-SVM	Gamma = 0.5; C = 1; Kernel = rbf	Scikit-learn
FFN-MLP	HL neurons = 50 HL activation function: <i>Tanh</i> OL activation function: softmax	PyBrain

HL: Hidden Layer; OL: Output Layer
Source: The authors

For each classifier, we progressively changed the dataset size and used the k-fold cross-validation technique [40] with $k = 10$ in each iteration, to measure the learning and test precision/error. This allowed us to evaluate the performance variation (standard deviation) of each classifier. Table 2 shows the mean and standard deviation of precision of training and testing for each classifier. The highest scores are obtained by k-NN for training precision and by MLP for test precision. In contrast, the lowest precision is obtained by using Naïve Bayes in both the training and test stages.

Learning curves obtained for each classifier are shown in Figure 6. The shaded area around the learning curves indicates the standard deviation of training error for 10 iterations per step.

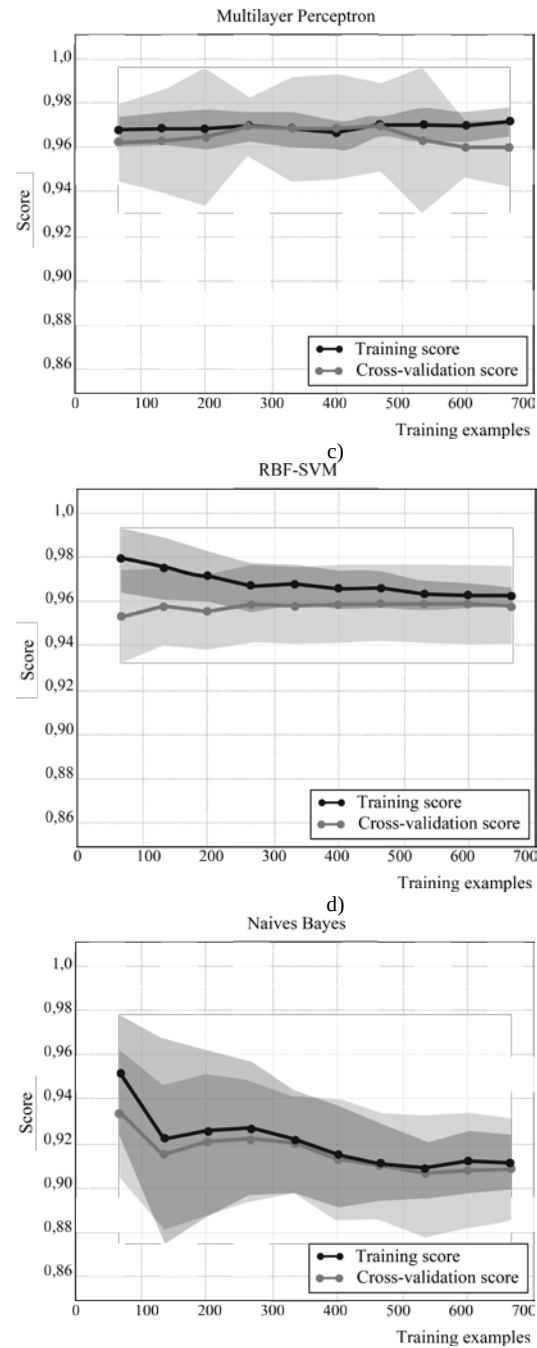
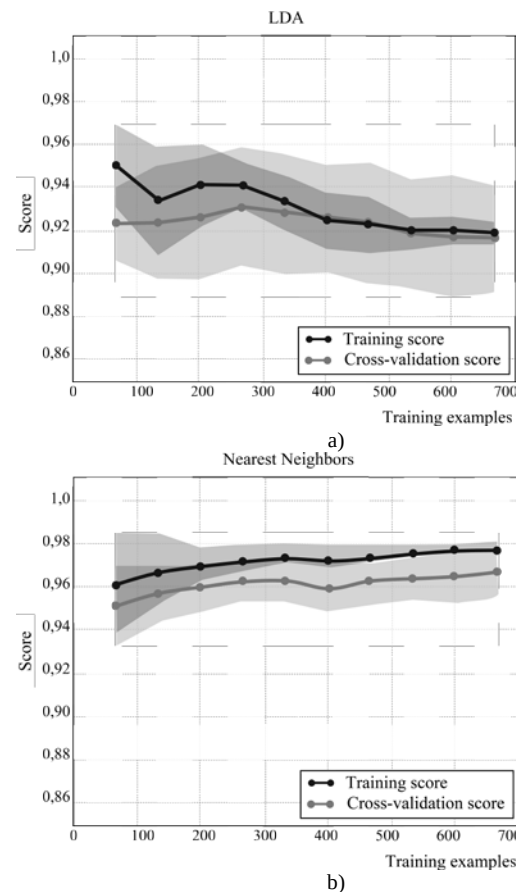
As shown in Figure 6c and Figure 6d, MLP and SVM are the most stable classifiers, as the learning and test curves do not show large differences when the training sample size is varied. MLP and k-NN achieve the highest scores in the training and test stages, but MLP presents high variation when using cross-validation (green shadow).

Table 2.

Mean and standard deviation of classifier precision for training and test stages.

Classifier	Training Precision		Test Precision	
	Mean	Std dev.	Mean	Std dev.
k-NN	0.9718	0.0072	0.9610	0.0115
Naïve Bayes	0.9202	0.0244	0.9153	0.0268
RBF-SVM	0.9678	0.0078	0.9574	0.0101
LDA	0.9304	0.0133	0.9235	0.0259
MLP	0.9688	0.0069	0.9646	0.0209

Source: The authors.



e) Figure 6. Learning curves for the binary classifiers used. Red and green lines, respectively, represent the training and cross-validation scores obtained when varying the training sample size.
Source: The authors.

LDA (Figure 6a) and Naïve Bayes (Figure 6e) have the highest variations in training and test scores, which means that more iterations are required to train a good classifier.

3.2. Fusion quality

A total of 30 pairs (near and far focused) of input images were fused using the proposed scheme. Fused images were

evaluated using the fusion quality metrics detailed in Section 2.6. The mean fusion quality for each classifier over 30 cases is shown in Table 3.

The Naïve Bayes classifier obtained the highest quality score for the VIFF and Qabf metrics, and MLP obtained the highest quality score for the FMI metric among all classifiers.

The high mean fusion quality achieved by MLP is expected because this classifier obtained the highest test score, as shown in Table 2. On the contrary, Naïve Bayes achieved the lowest training and test scores (Table 2) out of

all classifiers, but the highest fusion quality according to two out of three metrics among all classifiers (Table 3).

Some examples of the fusion results of the classifiers with the best results (Naive Bayes and MLP) are presented in Figure 7. Subtle differences in the masks generated from both classifiers can be observed. A qualitative judgment about this result is that MLP generates fewer artifacts than Naive Bayes.

Differences in fusion quality can be observed near the borders of objects, where artifacts are present due to the ambiguous nature of focus of the borders of objects in a natural scene (Fig. 8).



Figure 7. Results of image fusion scheme proposed for classifiers with the best fusion results: Naive Bayes and MLP. Column 1) input image 1; column 2) input image 2; column 3) Naive Bayes: near focus plane mask; column 4) MLP: near-focus plane mask.

Source: The authors.

4. Conclusions

The results obtained in the previous section show that the automatic classification concept can satisfactorily address the MFIF problem; that is, a classification scheme can be used to decide whether an image is focused or defocused based on local features. Thus, using this classification scheme, a fused image can be generated in which most regions or pixels are focused. The main contribution of this work is that it compares different classifiers in an MFIF scheme, thus evaluating which one obtains the best results in both learning and fusion stages. However, this work only evaluates the main classifiers found in the literature, and other classifiers not evaluated in this work may obtain better results.

Table 3.

Average fusion quality obtained with different classification methods

Quality Metric	FFN-MLP	LDA	Naïve Bayes	k-NN	RBF-SVM
VIFF	0.9258	0.9258	0.9259	0.9253	0.9246
Qabf	0.7572	0.7509	0.7573	0.7569	0.7564
FMI	0.6089	0.6083	0.6084	0.6083	0.6078

Source: The authors.

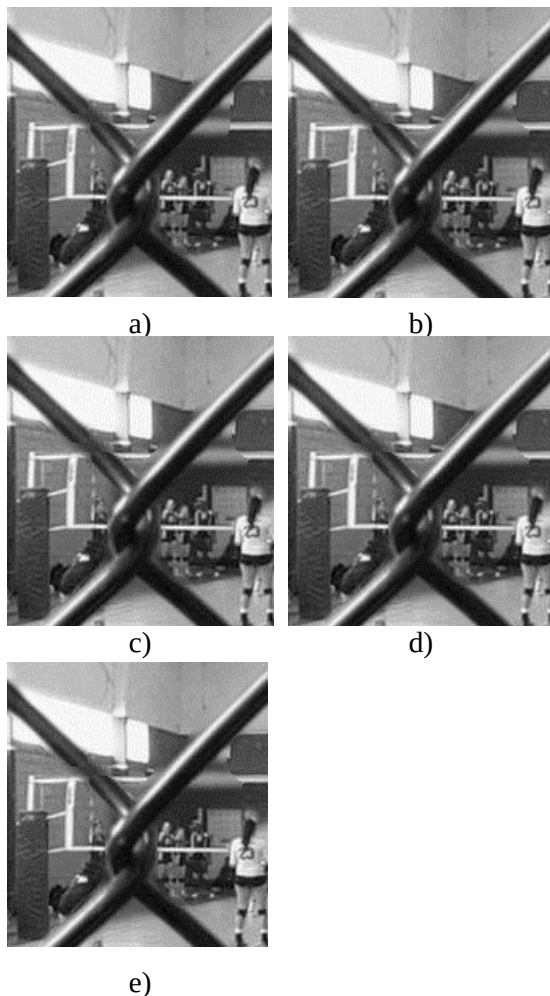


Figure 8. Magnified regions of fusion results obtained by a) FFN-MLP; b) k-NN; c) LDA; d) Naïve-Bayes; and e) RBF-SVM.

Source: The authors.

The most important conclusions obtained from this work are as follows:

- Classification precision does not guarantee fusion quality; that is, a classifier can have a low training and testing score but a high fusion quality.
- Naïve Bayes is an example of the latter. It is well known that Naïve Bayes is a robust classifier, and thus, subject to overfitting problems. Thus, it can perform well with small amounts of training data, which is the case found in this work. It is possible that this can be related to the number of artifacts a classifier generates and therefore the fusion quality.
- The MLP classifier shows good results in both the classification stage (training and test) and the fusion stage (fusion quality).
- Artifacts are generated near the borders of objects in the scene due to the spatial nature of the scheme used and the rectangular shape of the moving window. A good classifier generates fewer artifacts in these regions.
- MFIF is not a trivial problem, and a specific classifier can directly affect the fusion quality obtained using the proposed scheme in this work.
- Both the size of the moving window and kernels for morphological operations directly affect the results. Thus, future work should focus on evaluating the impact of these parameters on fusion quality obtained by this scheme.

Furthermore, the scheme proposed in this work could be adapted to address multi-focus scenes that present more than two (near and far) focal depths. An optimization technique based on region-growing could thus be used to generate a better smoothed mask Z' that encloses the objects that appear in the scene more precisely.

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Foliar content of N, P and K in cotton fertigated with treated sewage effluents

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Abstract

The objective of this study was to evaluate the effects of irrigation with treated sewage effluent in the leaf content of nitrogen, phosphorus and potassium in cotton (*Gossypium hirsutum* L. cultivar 8H) growing in two soil types. The experiment was carried out on the campus of the Federal University of the Semi-Arid Mossoró, Brazil. The experimental design was a randomized block with split plots. Treatments consisted of dilutions of domestic sewage effluent with water-supply [25, 50, 75 e 100% effluent and, water-supply + mineral soil fertilization - control] in two different types of soils textures (Oxisol and inceptisol). We conclude that the use of treated sewage effluent supplies the nutritional needs of growing cotton in relation to N and K, except for P.

Keywords: *Gossypium hirsutum* L.; wastewater; fertirrigation.

Contenido foliar de N, P y K en algodón fertirrigado con efluente de alcantarillado tratado

Resumen

El objetivo de este trabajo fue evaluar los efectos del riego con efluente de alcantarillado tratado en el contenido foliar de nitrógeno, fósforo y potasio en el cultivo de algodón (*Gossypium hirsutum* L. cultivar 8H) en dos tipos de suelos. El experimento fue llevado a cabo en el Campus de la Universidad Federal del Semi-Árido en Mossoró, Brasil. El diseño experimental empleado fue el de bloques al azar con parcelas subdivididas. Los tratamientos consistieron en diluciones del efluente de alcantarillado en agua de abastecimiento [25, 50, 75, 100% de efluente y tratamiento agua de abastecimiento + fertilización mineral del suelo - control] en dos tipos de suelos con diferentes texturas (Latossolo Vermelho Amarelo y Cambissolo). Se concluye que el uso de aguas residuales suple las necesidades nutricionales del cultivo de algodón en lo referente al N y K, excepto para el P.

Palabras clave: *Gossypium hirsutum* L.; agua residual; fertirrigación.

1. Introducción

Este artículo es parte de la disertación de Maestro del primer autor, presentado en el Programa de Posgrado en Ciencias del Suelo Del UFERSA– Mossoró, RN, Brasil.

La escasez de agua de buena calidad es una realidad actual y

creciente, puesto que se trata de una cuestión ambiental, que es afectada por y las actividades de urbanización, deforestación, agricultura, pecuaria e industria, principalmente cuando implica algún tipo de contaminación, comprometiendo el consumo de agua para las futuras generaciones.

La producción agrícola depende de la disponibilidad de

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agua y del uso racional, fundamentalmente en las áreas donde este recurso es escaso. En consecuencia la utilización del agua para riego es un desafío relevante para las regiones áridas y semiáridas, constituyéndose en un serio problema para el desarrollo de esas regiones.

Por tanto, es necesario buscar alternativas racionales que viabilicen el uso de las aguas residuales, considerando criterios ambientales, sociales y económicos, puesto que a cada día se hace más necesario la búsqueda de fuentes alternativas.

La reutilización de las aguas residuales constituye una práctica de carácter benéfico que puede ser abordado de varias formas. Se destaca la utilización de estas aguas en la práctica del riego, principalmente en cultivos cuyo producto no se destina para fines comestibles, por ejemplo cultivos de oleaginosas para la producción de biodiesel, tales como el algodón (*Gossypium hirsutum* L.), el ricino (*Ricinus communis* L.) y el piñón de tempate (*Jatropha curcas* L.).

Según Van der Hoeck et al. [29] una de las ventajas de la utilización de las aguas residuales en el riego es la posibilidad del aporte y el reciclaje de nutrientes, reduciendo considerablemente la aplicación de fertilizantes, además de la preservación ambiental y economía del agua de buena calidad. De esta manera, el uso de estas aguas posibilita, además del suministro hídrico, abastecer parte o la totalidad de las necesidades nutricionales de las plantas, hecho semejante al que ocurre en la fertirrigación, en la cual los nutrientes son aplicados a las plantas a través del agua de riego.

Azevedo et al. [1] verificaron que el agua residual tratada contribuye a la obtención de mayor producción y mejor calidad de las fibras de algodón, probablemente debido al potencial nutricional de los efluentes. Además, varios trabajos indican que el efluente tratado usado para el riego, es importante desde el punto de vista nutricional para cultivos como pimentón [26], arroz [27], plántulas de flamboyant [12], girasol [16] y gerberas [14].

En general, los efluentes municipales presentan contenidos de macronutrientes suficiente para atender la demanda de los cultivos, por eso se constituyen en una importante fuente de fertilizantes, mejorando el rendimiento de los cultivos. Sin embargo, se debe considerar las exigencias nutricionales de cada cultivo y el tipo de suelo. El nitrógeno, el fósforo y la materia orgánica contenidos en los efluentes tratados son fertilizantes y acondicionadores del suelo, favoreciendo el desarrollo de las plantas [8].

A pesar de varios beneficios evidenciados, el riego con aguas residuales puede llevar a la acumulación en el suelo de otros elementos tales como metales pesados, ocasionando contaminación ambiental, por eso el uso de estas aguas requiere un manejo adecuado, puesto que además de presentar considerables concentraciones de iones disueltos como el sodio, boro y cloruros, contiene gran variedad de organismos patógenos como bacterias, virus, protozoarios y helmintos. Tales características dificultan la utilización de aguas servidas (aguas residuales) en la agricultura [6,27].

Por otro lado, existen pocas publicaciones científicas relacionadas al tema de la reutilización aguas servidas tratadas en el riego del cultivo de algodón, lo que contrasta con la importancia económica de este cultivo, especialmente

en lo que refiere a la escasez de recursos hídricos, ventajas y limitaciones de la reutilización en la región semiárida del Nordeste brasileño.

En este sentido, el trabajo tuvo como objetivo evaluar el efecto del riego con efluente secundario tratado, proveniente de aguas residuales domésticas, en el contenidos foliar de nitrógeno, fósforo y potasio en el cultivo de algodón (*Gossypium hirsutum* L., cultivar 8H) en dos tipos de suelos.

2. Materiales y métodos

El experimento fue llevado a cabo en el periodo comprendido entre noviembre de 2009 a marzo de 2010, en el área experimental del Departamento de Ciencias Ambientales y Tecnológicas de la Universidad Federal Rural do Semi-Árido (UFERSA), en Mossoró, Río Grande do Norte (RN), Brasil, localizado en las coordenadas geográficas de 5° 11' de latitud Sur y 37° 20' de longitud Oeste de Greenwich. El clima (de acuerdo con la clasificación de Köppen) es del tipo BSw_h, siendo la precipitación media anual de 678 mm. Las medias anuales de temperatura, insolación y humedad relativa son 27,4 °C, 2360 horas anuales y 68,9%, respectivamente [4].

El esgoto doméstico tratado (secundario) provino de la laguna de estabilización de la Estación de Tratamiento de Esgotos Domésticos das Cajazeiras en Mossoró, RN, perteneciente a la CAERN (Compañía de Agua y Esgoto de Rio Grande do Norte), ubicado en la comunidad de Passagem de Pedras. Dicho efluente fue transportado semanalmente de la laguna de estabilización hasta el lugar del experimento en tanques de 1000 L, siendo este volumen suficiente para la preparación del agua de riego, durante una semana. El agua potable provino del sistema de abastecimiento público del campus de la UFERSA. Los resultados de los análisis físico-químicos y microbiológicos del esgoto doméstico se muestran en la Tabla 1.

La variedad de algodón utilizado fue 8H utilizaron cuarenta y ocho semillas por subparcela, con dos líneas de veinticuatro, sembradas en forma equidistante a una profundidad que varió entre 2,5 a 3,0 cm, con la finalidad de evaluar la influencia de los tratamientos en la germinación del cultivo.

Tabla 1.

Características del efluente de esgoto tratado utilizado para el riego.

CARACTERÍSTICAS	UNIDADES	EFLUENTES
pH		7,4
Conductividad eléctrica	dS m ⁻¹	1,75
Amonio	mg L ⁻¹	20,16
Nitrato (NO ₃ ⁻)	mg L ⁻¹	0,07
Nitrito (NO ₂ ⁻)	mg L ⁻¹	0,007
Nitrógeno orgánico	mg L ⁻¹	0,64
Nitrógeno total	mg L ⁻¹	17,31
Calcio	mg L ⁻¹	181,44
Sodio	mg L ⁻¹	33
Magnesio	mg L ⁻¹	21,86
Potasio	mg L ⁻¹	8,5
Fósforo	mg L ⁻¹	3,16
Cloruro	mg L ⁻¹	350
RAS	mmol L ^{-1,05}	7,02
DBO	mg L ⁻¹	35,28
Coliformes totales	NMP100 ml	1,1 x 10 ⁶
Cobre	mg L ⁻¹	0,133
Fierro	mg L ⁻¹	0,18
Manganeso	mg L ⁻¹	0,073
Zinc	mg L ⁻¹	0,033

Fuente: Elaborada por los autores.

El diseño experimental empleado fue el de bloques al azar con parcelas subdivididas. A nivel de parcelas se probaron diferentes diluciones del efluente de alcantarillado en agua de abastecimiento: 25, 50, 75, 100% de efluente (T_1 , T_2 , T_3 y T_4 , respectivamente) y tratamiento agua de abastecimiento + fertilización mineral del suelo – control (T_5) y como subparcelas se consideraron dos tipos de suelos de textura contrastante: Latossolo Vermelho Amarelo y Cambissolo (S_1 y S_2 , respectivamente). Los tratamientos fueron dispuestos en 20 parcelas experimentales con un área de 1 m² (0,50 m x 2,00 m), siendo cada parcela fue subdividida en dos subparcelas (suelos), totalizando 40 unidades experimentales, constando de cinco diluciones, dos tipos de suelos y cuatro repeticiones.

Cada subparcela estuvo compuesta por dos hileras de plantas, con ocho plantas por metro lineal, espaciados en 0,15 m entre hileras y 1 m entre subparcelas. En cada subparcela, se consideraron solamente las plantas centrales. Los tratamientos fueron aislados con plástico (polietileno) hasta una profundidad de 0,50 m, para evitar posibles contaminaciones entre los tratamientos. Las parcelas experimentales fueron divididas con paredes de ladrillo, y posteriormente llenadas con 315 kg de suelo arenoso (S_1) y 288 kg de suelo arcillosos (S_2).

Se retiraron submuestras de cada tipo de suelo para la caracterización física (granulometría, densidad aparente y porosidad) siguiendo metodologías recomendadas por la EMBRAPA [7]. Además, se determinó la capacidad de retención de agua de los dos suelos, siendo que esa información fue utilizada en la planilla de riego.

Los análisis físicos y químicos del suelo (Tabla 2 y Tabla 3) fueron realizados antes del inicio de la etapa experimental, con el objetivo de obtener información para efectuar la fertilización, en función a la cantidad de nutrientes existentes del suelo y requerimiento del cultivo.

De manera previa a la incorporación de piedra caliza al suelo, se elevó la humedad del suelo hasta capacidad de campo. Se procuró realizar una mezcla homogénea de piedra caliza en el suelo, puesto que se tenía disponible un periodo de 15 días para la reacción.

Después de realizar el encalado del suelo, se determinó la necesidad de fertilización de fondo y de cobertura para el tratamiento en que se utilizó agua de abastecimiento para el riego, según la recomendación de la EMBRAPA [7] para el cultivo de algodón herbáceo cultivado en la zona del Cerrado.

Tabla 2.
Características físicas de los suelos utilizados.

Suelo	Densidad (kg dm ⁻³)	Porosidad (%)	Arena	Limo g kg ⁻¹	Arcilla
“Latossolo”	1,4	45,95	920	30	50
“Cambissolo”	1,28	52,58	590	180	230

Fuente: Elaborada por los autores.

Tabla 3.
Características químicas de los suelos utilizados.

Suelo	pH	Mat. org (%)	P	K mg dm ⁻³	NA	Ca + Mg	Al cmolc.dm ⁻³	(H+Al)	CTC	PST (%)
“Latossolo”	5,8	0,32	4,2	39,3	1	0,5	0	2,31	2,91	0
Cambissolo	6,7	0,95	7,2	378,2	21,9	9,9	0	1,16	12,12	1

Fuente: Elaborada por los autores.

De acuerdo con los contenidos en los suelos y una producción esperada de 5 t ha⁻¹, se utilizaron dosis de fertilización de fondo con N y P de 25 kg ha⁻¹ y 90 kg ha⁻¹, respectivamente. En el caso del K, fue necesaria la aplicación de 30 kg ha⁻¹, solamente para el suelo arenoso. Adicionalmente se aplicó azufre a razón de 40 kg ha⁻¹, mediante el sulfato de magnesio, para los dos tipos de suelos toda vez que el algodón es bastante exigente a este elemento.

Para la fertilización de cobertura se aplicaron 125 kg ha⁻¹ de N para los dos tipos de suelos, y en el caso del K 140 kg ha⁻¹ para el suelo arenoso. La aplicación de cobertura fue dividida en dos etapas: en la primera, a los 25 días después de la emergencia (DDE) se aplicó la mitad del N y 40% del K recomendados; en la etapa 2 se aplicó el resto del N y el K, en el inicio de la floración (a los 50 DDE). Los otros tratamientos recibieron estos elementos en la “fertilización” con agua residual, hasta los 100 DDE. La piedra caliza fue incorporada manualmente a una profundidad media de 25 cm, en tanto que para la fertilización de fondo, los nutrientes fueron aplicados en surcos a una profundidad aproximada de 10 cm. La fertilización de cobertura fue realizada también mediante la “fertilización”.

Para el suministro del agua de riego se utilizó el sistema de riego localizado, utilizándose emisores tipo microtubos de 1,5 mm de diámetro interno, para evitar el taponamiento por las partículas en suspensión presentes en el efluente. La aplicación del agua + fluente fue realizada utilizándose reservorios individuales con capacidad de 310 L, instalados encima una estructura construida con ladrillos y madera, de tal forma de obtener una columna de agua de 1,2 m. Dichos reservorios fueron llenados semanalmente con los volúmenes correspondientes a cada tratamiento.

La determinación de los contenidos de N, P y K en las hojas fue realizada en dos épocas (a los 70 y 115 DDE), mediante el método de extracción por digestión sulfúrica. Para ello, se utilizó 0,4g de materia seca, que fue digerida en 4 mL de ácido sulfúrico, 2 mL de peróxido de hidrógeno y 0,7g de una mezcla digestora compuesta de sulfato de sodio, sulfato de cobre y selenio, en una proporción de 100:10:1, colocado en el bloque digestor durante una hora a una temperatura de 250 °C hasta alcanzar una coloración castaña y después de ese tiempo la temperatura fue elevada a 350°C hasta obtener una coloración verdosa, obteniéndose los extractos que fueron completados hasta un volumen de 50 mL. El bloque digestor utilizado tenía una capacidad para 40 tubos de ensayo, lo que permitió analizar 39 muestras más un tubo de ensayo conteniendo solamente reactivos como prueba en blanco.

En el extracto sulfúrico se cuantificó el nitrógeno por el método de Kjeldahl y el potasio por fotometría de emisión de llama, siguiendo la metodología citada por Tedesco et al. [28] y el fósforo por espectrofotometría, basado en el método de determinación de Braga y Defelipo [3].

Tabla 4.

Resumen del análisis de varianza de los contenidos de N, P y K en función de la fertirrigación con y sin agua residual en dos tipos de suelos a los 70 y 115 DDE. Mossoró-RN, 2010.

F.V.	G.L	Cuadrados medios					
		70 DDE			115 DDE		
		N	P	K	N	P	K
PAR	4	27,240n.s	0,324n.s	41,441*	6,425n.s	0,438n.s	3,769*
Suelo	1	128,343 *	0,289n.s	112,828*	62,555n.s	2,402**	9,890*
PARx Suelo	4	18,030n.s	0,591**	9,719**	38,59n.s	0,615n.s	2,99**
Residuo	27	12,555	0,591	3,38	27,721	0,354	0,498
C.V (%)		9,53	26,04	12,53	15,87	47,51	12,33

PAR – Proporción de agua residual; ** - significativo a 1% de probabilidad; * - significativo a 5% de probabilidad; ns – no significativo por la prueba de F.

Fuente: Elaborada por los autores.

Las medias de los resultados fueron comparadas por la prueba de F (al nivel de 5%), utilizándose para ello el del programa SISVAR.

3. Resultados y discusión

De acuerdo con el análisis de varianza (Tabla 4), donde se considera los contenidos de N, P y K en la hoja a los 70 DDE, se verificó que hubo una interacción significativa entre las proporciones de agua residual aplicadas y los tipos de suelos para los contenidos de P y K al nivel de 5% de probabilidad, y efecto significativo independiente para las proporciones de agua residual únicamente para el contenido de K. Con relación a la fuente de variación tipo de suelo ocurrió un efecto significativo para el N y el K al nivel de 1% de probabilidad.

Con relación a la segunda colecta realizada 115 DDE, se observó una interacción significativa únicamente para el K en todas las fuentes de variación estudiadas. Ocurrió un efecto aislado del tipo de suelo para el P y K, y efecto significativo de las proporciones de agua residual solamente para el K.

3.1. Nitrógeno

En el “Latossolo” a los 70 DDE, se verificó que el contenido de nitrógeno fue mayor cuando las plantas fueron fertirrigadas con 100% de agua residual (39,66 g kg⁻¹), en la cual se obtuvo un incremento de 17% comparado con el tratamiento control T₅. Los otros tratamientos (T₁, T₂ y T₃) presentaron contenidos medios de 32,59; 36,16 y 35,44 g kg⁻¹, respectivamente (Fig. 1A). En el “Cambissolo”, se observaron mayores valores de N para los tratamientos T₃, T₄ y T₅.

De acuerdo con la misma Figura, se puede evidenciar que pese a que no existe una diferencia significativa, los valores medios de N obtenidos en los dos tipos de suelos se encuentran próximos al rango observado por Yamada et al. [30], considerados adecuados para el cultivo de algodón de alta productividad (40 - 45 g kg⁻¹). Siendo importante resaltar que en este período, el contenido de N disponible para la planta utilizando agua residual es suficiente para atender la demanda del cultivo, toda vez que este nutriente es requerido en gran cantidad por el algodón, durante las fases vegetativa y de florecimiento.

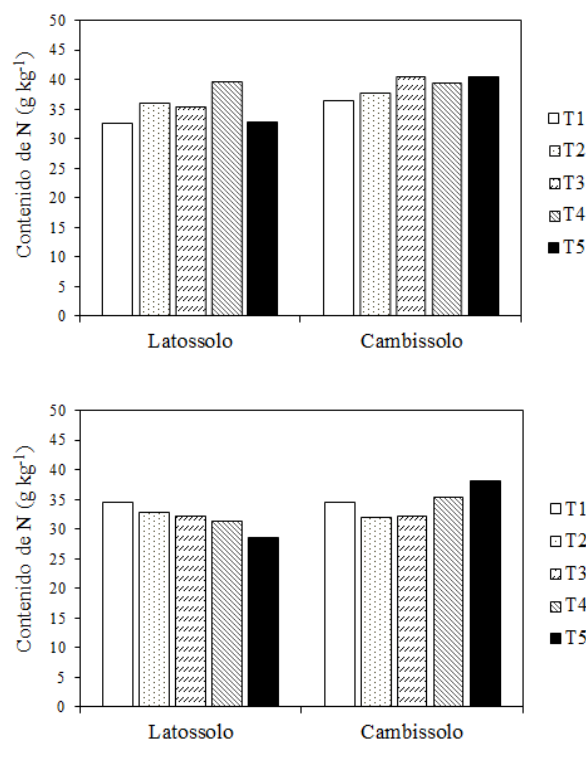


Figura 1. Contenido de N (A) a los 70 DDE y (B) a los 115 DDE. Fuente: Elaborada por los autores.

En el suelo “Latossolo” a los 115 DDE, se observa un decremento en los contenidos de N en las plantas fertirrigadas con el aumento de las proporciones de agua residual; empero, las plantas que fueron sometidas al T₁ presentan valores superiores al T₅, registrándose un incremento de 17% (Fig. 1B). Para el “Cambissolo”, se obtuvieron mayores contenidos de N para las plantas que recibieron el T₅, con 38,11 g kg⁻¹ y menores para los tratamientos T₂ y T₃, con 31,96 y 32,22 g kg⁻¹, respectivamente. Se observó también un incremento de N en las plantas, en el orden de: 10,72; 4,11; 12,62 y 18,55% sometidas a los tratamientos T₁, T₂, T₃ y T₅, comparado con las plantas cultivadas en el “Latossolo”. Esto puede ser explicado por la mayor disponibilidad de nutrientes para la planta en el “Cambissolo”, en virtud de que este suelo presenta mayor cantidad de materia orgánica, además de poseer una mayor capacidad de retención de sales provenientes del agua residual.

Los resultados encontrados discrepan de alguna manera con los obtenidos por Fonseca et al. [10], usando efluentes en el riego de maíz, puesto que indica que el efluente contribuye para el aumento del contenidos de N en las plantas, incluso más altos que de las plantas cultivadas con el manejo convencional. Por otro lado, confirman los obtenidos por Damasceno [5] cuando cultivó la gerbera fertirrigada con efluentes domésticos tratados con y sin suplementación mineral, quien no observó grandes concentraciones de nutrientes en las hojas de las plantas. Ricci [20] también no obtuvo diferencias en las concentraciones de nutrientes en la parte aérea de la planta cuando comparó fertilización orgánica y convencional.

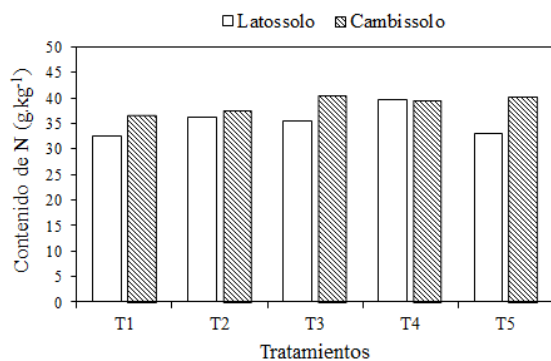


Figura 2. Totales en el limbo foliar del algodón fertilizado con agua residual y fertilización mineral.

Fuente: Elaborada por los autores.

Asimismo, en la evaluación de los dos tipos de suelos durante el ciclo del algodón, se percibió mayor respuesta en las plantas cultivadas en el “Latossolo”, en virtud de este suelo presenta menor contenido natural de materia orgánica y nitrógeno. Se constató también que este nutriente aumentó en función del mayor aporte de materia orgánica por el agua residual (Fig. 2).

3.2. Fósforo

Hubo interacción significativa entre los factores estudiados para el contenido de fósforo a los 70 DDE (Tabla 4). En esta misma época, se evidenció que las plantas de algodón que fueron sometidas a los tratamientos T₁, T₂, T₃ y T₄ y cultivadas en el suelo S₁ (“Latossolo”) presentaron incrementos de 27,8; 39,0; 37,3 y 40,11% comparados al tratamiento control (T₅), demostrando que la aplicación de aguas residuales aumentó los niveles de ese nutriente en las plantas cultivadas en el “Latossolo” (Fig. 3). Esto puede ser explicado mediante la cantidad encontrada de fósforo en el suelo, que era bajo, obteniendo así mejor respuesta para los tratamientos con agua residual. En tanto que en el “Cambissolo”, se obtuvo un comportamiento inverso en las plantas cuando fueron sometidas al tratamiento T₅, en el cual se obtuvo mayores contenidos de P (comparado con las plantas que fueron cultivadas con 100% de agua residual (T₄)). Este hecho puede ser explicado debido a que este suelo presenta mayor capacidad de retener ese nutriente, en razón a su mayor capacidad de intercambio catiónico (CIC), según el análisis de fertilidad realizado al inicio del experimento (Tabla 3).

Los resultados de los análisis de los tratamientos en el “Latossolo” a los 115 DDE, muestran que las plantas que recibieron agua residual presentaron valores muy próximos a plantas que no recibieron (control) (Fig. 4). En tanto que en el “Cambissolo” se constató un incremento en el P acumulado a medida que se aumenta el porcentaje de agua residual en la solución aplicada, sin embargo, el tratamiento T₅ y T₄ fueron los que presentaron mayores valores de este nutriente (1,25 g kg⁻¹). Tal hecho se debe a la cantidad de fósforo del agua residual, y a la mayor CIC del suelo arcilloso, consecuentemente su capacidad de retener mayores cantidades de nutriente.

Analizando los efectos de los tratamientos con y sin agua residual en los suelos estudiados, se verificó que la mejor respuesta de las plantas a la acumulación de ese nutriente fueron

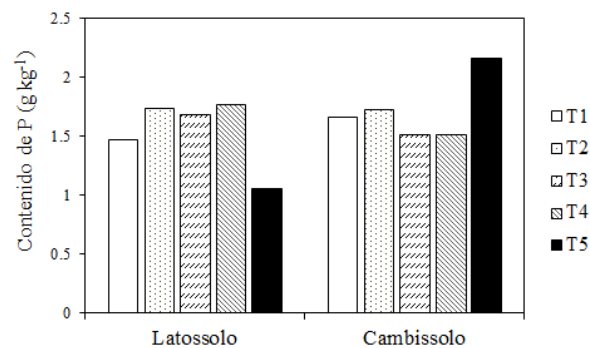


Figura 3. Contenidos de P a los 70 DDE.

Fuente: Elaborada por los autores.

en aquellas cultivadas en un suelo arcilloso (“Cambissolo”), donde se destacó el tratamiento convencional, o sea, sin agua residual (T₅) con ganancia porcentual de 30% en comparación con T₄ (Fig. 5). Los contenidos medios en todo el experimento variaron entre 1,06 y 1,77 g kg⁻¹ para el “Latossolo” 1,52 a 2,16 g kg⁻¹ para el “Cambissolo”. No obstante, los valores encontrados para el “Cambissolo” fueron superiores al “Latossolo”, donde están próximos al rango inferior al recomendado por Rosolem et al. [21] que obtuvieron contenidos entre 2,3 y 2,6 g kg⁻¹. Siendo que el rango obtenido en este experimento se encuentra debajo de los resultados obtenidos por Serra et al. [23].

Estos resultados concuerdan con los obtenidos por Silva Júnior et al. [24] para el cultivo de banana, también verificaron que los tratamientos con agua residual no difirieron del testigo, el cual presentó un valor medio de 1,17 g kg⁻¹. Según Brady [2] la disponibilidad de P para los vegetales es determinada razonablemente por la forma iónica de ese elemento y está determinada por el pH de la solución en la que se encuentra este ión.

El fósforo es un nutriente de alta demanda por el algodón, puesto que estimula el crecimiento radicular, florecimiento y desarrollo de los frutos. Al contrario del N, que prolonga la fase vegetativa de las plantas, el fósforo favorece a la maduración de los capullos, aumenta el rendimiento y la calidad de la fibra [15].

Por tanto, una de las alternativas para la producción de algodón es la fertilización vía orgánica, con el uso de aguas residuales, y la suplementación a través de la fertilización mineral con fósforo, de acuerdo con la fase fenológica de la planta.

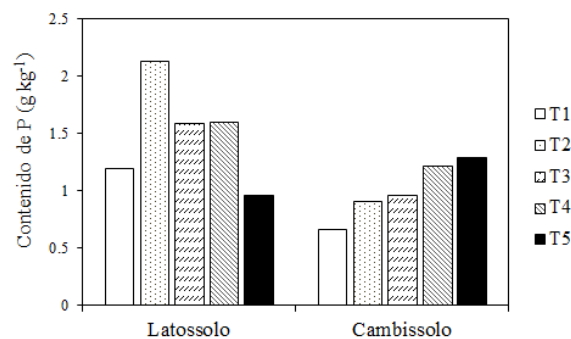


Figura 4. Contenidos de P a los 115 DDE.

Fuente: Elaborada por los autores.

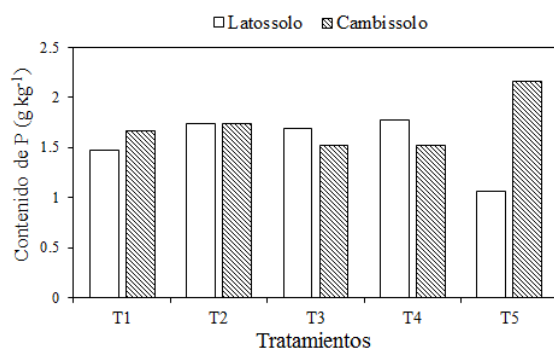


Figura 5. Totales en el limbo foliar de algodón fertirrigado con agua residual y fertilización mineral.

Fuente: Elaborada por los autores.

3.3. Potasio

En el caso del Potasio se observó el efecto de la interacción entre las proporciones de agua residual y los dos suelos estudiados en las diferentes épocas de colectas, donde se percibió que en el “Latossolo” las parcelas que recibieron proporciones de efluentes a los 70 DDE presentaron mayores valores comparados con el tratamiento con fertilización mineral, en la cual se destacó el T₂ con 25% de agua residual (21,2 g kg⁻¹), obteniéndose un incremento de 41% con relación al T₅ (Fig. 6). Tal hecho puede ser explicado por las características químicas y físicas de este suelo, sumado a la cantidad de este nutriente aplicado en la fertirrigación, permitiendo así mayor extracción del potasio por la planta. Empero, para el “Cambissolo”, se percibió que las plantas tratadas con T₁, T₂ y T₃ presentaron valores ligeramente superiores de potasio al comparar con las plantas de los tratamientos T₄ y T₅, promoviendo un incremento cercano al del 21%.

A los 115 DDE se evidenció que el contenido de K en el “Latossolo” presentó pequeñas variaciones entre los tratamientos, variando de 4,26 a 5,95 g kg⁻¹. Por otro lado, en el “Cambissolo” se verificó una mayor diferencia entre tratamientos con relación a la acumulación de este nutriente, ocurriendo una reducción de 28% para el tratamiento control (T₅) comparado con el T₂ (Fig. 7A). El contenido de K en la segunda colecta están muy debajo de lo recomendado por Silva et al. [25], que es de (15 a 25 g kg⁻¹) para las hojas del algodón, encima de 90 DDE. Sin embargo, el contenido en las hojas puede caer progresivamente con el ciclo de la planta [18]. Es importante resaltar que, el algodón acumuló altas concentraciones de K en sus hojas antes de la floración, ocurriendo reducciones significativas después de ese período. También se observó que la concentración de potasio en la hoja es fuertemente influenciado por la edad de la hoja muestreada y por la fase fisiológica de la planta. De acuerdo con Feigin et al. [9], cuando utilizaron efluente y agua tratada en el riego de algodón no observaron diferencias significativas entre los tipos de agua para contenidos de N, P y K, sin embargo, verificaron que hubo una mayor acumulación de K en las plantas regadas con efluente.

Pese a que se registraron bajos contenidos de potasio en la segunda colecta de plantas, se observó que los valores encontrados en ambos suelos, están dentro el rango recomendado por Silva et al. [25] Además, los valores encontrados para los tratamientos con agua residual fueron

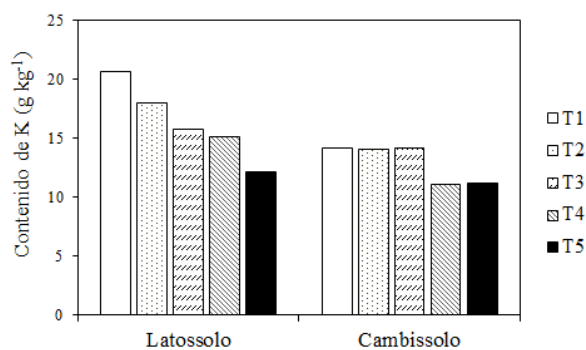
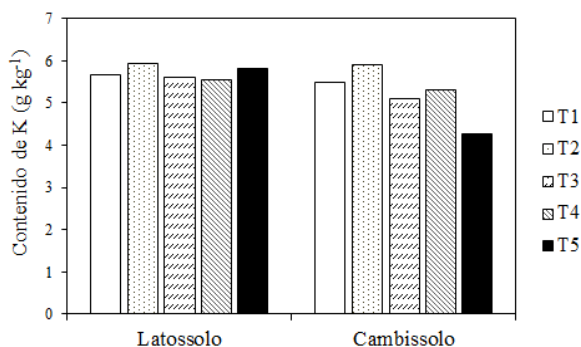
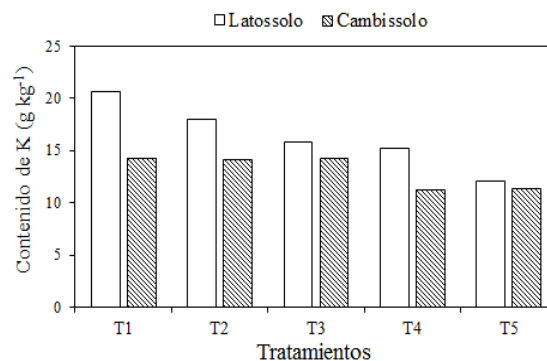


Figura 6. Contenido de K a los 70 DDE.

Fuente: Elaborada por los autores.



A



B

Figura 7. Contenido de K a los 115 DDE (A) y (B) totales en el limbo foliar de algodón fertirrigado con agua residual y fertilización mineral.

Fuente: Elaborada por los autores.

superiores al convencional. Comprobándose de esta manera la eficiencia del uso de efluentes en la fertirrigación, trayendo como consecuencia un aumento del contenido de este nutriente en el cultivo de algodón, así como en otros cultivos tales como el maíz y frijol [17], caña de azúcar [13], gerbera [14] y ricino [11], comprobando la viabilidad de la fertilización con agua residual.

De acuerdo a los resultados obtenidos en el presente experimento hubo diferencias en los contenidos de N y P con relación al tratamiento control, constatándose un enorme beneficio para las plantas de algodón cultivadas con agua residual rica en nutrientes orgánicos, además de economizar el uso de agua de buena calidad.

Varios estudios demostraron que la aplicación de agua

residual elevó la concentración de macronutrientes en las hojas de las plantas cultivadas [22, 19] y que, de modo general, este aumento es influido por la concentración de nutrientes en el agua.

4. Conclusiones

La utilización de agua residual suple las necesidades nutricionales del algodón en N y K, excepto para P.

En base al contenido foliar de N y K, se concluye que las plantas de algodón regadas con efluente tratado y cultivadas en un suelo “Latossolo” mostraron mayor respuesta en la absorción de dichos nutrientes.

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4 microstructural, mechanical and wear characterization of Cu_0Al_2 coatings deposited via thermal spray

Williams et al.: Incañie' Cam\$os^a; hon;airo - la2a^a < ; ose = d1ar Al7onso' - r8uela^b

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Resumen

En este trabajo se caracterizó la microestructura, la adherencia y el coeficiente de desgaste de recubrimientos de Cu_0Al_2 depositados mediante spray térmico sobre sustratos de latón. En el estudio se utilizaron como parámetros de evaluación la preparación superficial del sustrato y un recubrimiento intermedio. Fue utilizada como capa adhesiva. El análisis de la composición química se hizo mediante la fluorescencia de rayos D-ERD#, el análisis estructural se realizó por medio de la difracción de rayos D-DRD# y la microscopía electrónica de transmisión. La adherencia se determinó mediante los ensayos de rayado transversales, la respuesta mecánica se evaluó mediante la medición de la dureza Gnoos y pruebas de desgaste abrasivo tres cuerpos y H in en disco. Los resultados permitieron establecer que el recubrimiento sin capa adhesiva y preparada por rallado metálico puede ser utilizado en la recuperación de piezas debido a que presenta menor falla cohesiva.

Palabras clave: Spray térmico; desgaste abrasivo; coeficiente de fricción.

Caracterización microestructural, mecánica y de desgaste de recubrimientos de Cu_0Al_2 depositados mediante spray térmico

Abstract

In this work, characterized the microstructure, adhesion and coefficient of wear of coatings of Cu_0Al_2 deposited via thermal spray on brass substrates. In the study, the surface preparation of the substrate and an intermediate coating were used as evaluation parameters. The analysis of the chemical composition was done by D-ERD# fluorescence structural analysis as performed by means of D-ray diffraction DRD# and transmission electron microscopy. Adhesion was determined by cross-hatch tests, the mechanical response was assessed by measuring the Gnoos hardness and abrasive wear tests three bodies and H in on disc. The results permitted to establish that the coating without adhesive layer and prepared by metal blasting can be used in the recovery of pieces because it presents less cohesive failure.

Keywords: Thermal spray; abrasive wear; friction coefficient

1. Introducción

En ingeniería la ciencia de materiales tienen entre sus objetivos mejorar el desempeño y rendimiento operativo de los componentes mecánicos. En su superficie existen diversos procesos de desgaste en su superficie. Para recuperar las piezas de equipos de uso industrial que han sufrido un deterioro, por

efectos, debido a procesos de corrosión, existen múltiples técnicas de recuperación y protección superficial, una de las cuales es la spray térmico. La TFF# es una técnica de recuperación que consiste en depositar sobre un sustrato, que se encuentra a temperatura ambiente material de la misma composición química o diferente a la del sustrato. El mecanismo de adherencia en esta técnica se basa en el anclaje mecánico.

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Una de las ventajas de esta t?cnica es su 1ran 7e0ibilidad \$ara \$roducir recubrimientos cer@nicos 2 met@licos I '4M= l objetivo de esta investi1aci>n se centr> en estudiar c>mo a7ecta el m?todo de \$re\$araci>n su\$er7icial del sustrato de lat>n C4(4" ", de uso naval, la adherencia, el coe7iciente de 7racci>n 2 de des1aste de los recubrimientos de una aleaci>n de Cu₀Al₂, comercialmente conocido como I ro0on ! %' + % Adem@, en al1unos sustratos se de\$osita> un recubrimiento intermedio de Al₀Ni₂, comercialmente conocido como I ro0on ! %' ! % con el 7n de determinar si me7bra la adherencia con relaci>n a los recubrimientos Aue no tienen este recubrimiento.

*e us> el Cu₀Al₂, debido a Aue se destaca \$or tener buenas \$ro\$iedades tribol>gicas 2 alta resistencia a la tensi>n, com\$arables con los aceros I4Madem@, estas aleaciones se utilizan comBnmente en a\$licaciones donde se desea incrementar la resistencia a la corrosi>n, como \$or e\$em\$lo, bu7es 2 com\$onentes del tren de aterri7a7e de aeronaves, com\$onentes de motores \$ara buAues de navelaci>n, 78aciones ba7o el a1ua, en la arAuitectura naval 2 en h?lices de los barcos. Fos bronce\$ al aluminio tambi>n se utilizan en 8o2er@ debido a sus \$ro\$iedades decorativas I&(M

Fi l+Mnvesti1> el com\$ortamiento al des1aste mediante el ensa2o de desli7amiento en seco N in' on' Dis1 O estableciendo una relaci>n l@nite de (+.) entre 7ases blandas 2 duras. Conclu2endo Aue si esta relaci>n es ma2or, el des1aste tiende a hacer deti\$o adhesivo \$resentando una 7ase PQlura, mientras Aue si la relaci>n es menor, el des1aste tiende a ser abrasivo \$resentando una 7ase R blanda. Adem@, 9 illiams I8M2 Goivuluoto I3M establecieron Aue e0iste una considerable incertidumbre sobre las caracter7icas microestructurales en la aleaci>n, en \$articular la distribuci>n de 7ases cristaloi1r@lcas dentro de la muestra. Un estudio similar donde se anali6> la relaci>n del m?todo de \$re\$araci>n con la adherencia 7ue hecho \$or : incasie I% M en este estudio se hi6o un recubrimiento de Cr< 2, sobre sustratos de lat>n naval 2 se determin> Aue el m?todo de \$re\$araci>n su\$er7icial de la muestra a7ecta la \$?rdida de volumen 2 Aue la ca\$a base disminu2e el coe7iciente de des1aste.

2. Producci3n de los recubrimientos

Fos sustratos usados 7ueron de lat>n naval UN* C4(4" " con dimensiones de ++, " D ! &4 D &" mm a los cuales se le reali7aron la \$rueba de des1aste A*T4 S (& I ara determinar la tasa de des1aste se reali6> la \$rueba de desli7amiento en seco en monedas con un di@metro de) " mm 2 un e\$esor de 4 " mm, si1uiendo la metodoloi7a reali7ada \$or S ee I% MFa lim\$ie6a se reali6> con acetona con el 7n de remover contaminantes como \$olvo 2/o 1rasas. Fos m?todos usados en la \$re\$araci>n de la su\$er7icie 7ueron. 1ranallado \$or arena, 1ranallado con alBmina 2 con disco abrasivo. I ara las \$robetas \$re\$aradas con el m?todo de 1ranallado se us> un eAui\$0 de 1ranallado marca FA4 =E re7erencia IAF4I., el cual se utili6> \$er\$endicular a las su\$er7icies a distancias entre % 2 %&mm. I ara el 1ranallado con arena se utili6> arena comercial, con un tama7o a\$ro0imado de \$artCula de ! " " Tm. =I \$roceso se reali6> con una \$resi>n de ", (3 4 I a 2 un tiem\$0 de %' s. I ara el 1ranallado con alBmina se utili6>

Tabla %

I ar@metros 2 caracter7icas de de\$>sito de los recubrimientos

Par@metro	Proxon 21071	Proxon 21021
I resi>n de o0leno 4 I a#	".4"	".4"
I resi>n de acetileno 4 I a#	". "+	". "+
I resi>n de aire com\$rimido 4 I a#	". "(	". "(
Distancia de \$ro2ecci>n mm#	%&'	%&'
Tama7o de \$olvo Um#	)! &	)! &
Tem\$eratura m@ima VC#	) +"	84"

Fuente: autores

alBmina con un tama7o de \$artCula de %' " Tm, a una \$resi>n de ", (3 4 I a, durante %' s; des\$u7s se \$ro2ect> alBmina con un tama7o de \$artCula a\$ro0imadamente de &' " Tm, ba7o las mismas condiciones de \$resi>n 2 tiem\$0. *e usaron dos tama7os de \$artCula, las \$artCulas de %' " Tm se usaron \$ara de7ormar la su\$er7icie 2 las \$artCulas de &' " Tm se utilizaron \$ara aumentar las cavidades donde se anclar@ el recubrimiento. I or Btimo, en el m?todo de disco abrasivo se utili6> un disco 7a\$ de %%('% ,&0 ! ! ,! & mm 2 1rano (" Tm 2 una \$ulidora WacJ DecJer, haciendo tres \$asadas \$or \$robeta, cada una con una duraci>n de %' s. Fos sustratos \$re\$arados 7ueron \$recalentados entre + " 2 8" VC en un horno el?ctrico, con el 7n de disminuir el choAue t?rmico entre los de\$>sitos 2 los sustratos; adem@ esto a2uda a mantener la su\$er7icie lim\$ia 2 libre de humedad. Fos recubrimientos de bronce al aluminio I ro0on ! %' + % 7ueron de\$ositados con un eAui\$0 de \$ro2ecci>n t?rmica con llama Castod2n D* 8" " " . =stos recubrimientos 7ueron de\$ositados con 2 sin ca\$a de adherencia conocida comercialmente como I ro0on ! %' ! % esta ca\$a es una aleaci>n de Ni ' %& Al. Fas condiciones de las \$ro2ecciones se resumen en la Tabla %

3. aracteri7aci3n de los recubrimientos

Fa ru1osidad de los sustratos se midi> con un ru1os3metro : ommel Tesler T' &' " calibrado con el est@dar D, N 4+++ 2 con un microscopio l@er con7ocal marca Yeiss re7erencia F*4 + " " con resoluci>n m@imade ! &' nm, \$ro\$orcionando im@enes a %' " D.

Fa com\$osici>n Au7nica de los recubrimientos se determin> con la t?cnica de 7uorescencia de ra2os 0 ERD# con un eAui\$0 4 ali0I ro I 9 ' ! 44" I hili\$e eAui\$ado con un tubo de Rodio, trabajando a una \$otencia de 4 J 9 , el an@isis semicuantitativo se reali6> con el so75 are, Z, haciendo %& barridos. Fa cristaloi1ra7a de los recubrimientos se caracteri6> \$or di7racci>n de ra2os D DRD# con un eAui\$0 D' sert I ro I anal2tical en modo ha6 rasante a &V, con la l@nea monocrom@ica GR del cobre %&4" 338[# trabajando a 4& J\ 2 4" mA. Fa microscop@ electr>nica de barrido 4 =W# se reali6> con un eAui\$0 E=, ZUANTA ! " " en alto vac@, o\$erando a una di7erencia de \$otencial de) " J\ 2 la microscop@ electr>nica de transmisi>n 4 =T# con un eAui\$0 marca Eei Tecnai ! " T5 in, o\$erando en el modo de di7racci>n, a una di7erencia de \$otencial de) " " J\ 2 una con constante de c@mara de ", +) " m. Fa dure7a de los recubrimientos se determin> mediante un eAui\$0 F=C- de re7erencia 4 ' 4 " " " S ! reali7ando ensa2os Gnoo\$ utilizando 4,3") N de car1a. I ara el ensa2o de desli7amiento en seco se \$ulieron los recubrimientos con varias li7as hasta lle1ar a la

li&a con tama&o de 1 rano % "" mesh# = n el ensa2o de N in' on' DisJO se utili6> un trib>metro C=TR' U4 T' ! ' %&'. = l ensa2o se reali6> con una es7era con radio de (,) & mm de Al₁-), con una dure&a de 8, %&3 S I a (& Rc# Fos \$ar@metros del ensa2o 7ueron. car1a de) .3! N, velocidad de (83 rev/se1, con una duraci>n de ("" s ecuaci>n % se1Bn la norma A*T4 D33.

$$V = \frac{\pi \cdot b^4}{64 \cdot R} \quad \% \#$$

siendo \ el volumen des\$la&ado, b es el ancho de la huella 2 R el radio de la es7era.

Fa \$rueba de abrasi>n a tres cuer\$os se reali6> ba&o la norma A*T4 S (& \$rocedimiento W. = l elemento abrasivo 7ue arena con una 1ranulometr&a de +, "+" Um secada en un cuarto con control de tem\$eratura \$or un d&a \$ara disminuir la humedad. I ara calcular el volumen removido se us> el estudio hecho \$or : utchin1s I% M2 las recomendaciones de la A*4 I% Men donde se relaci>n la 1eometr&a de la huella de&ada con el volumen removido.

I ara calcular la tasa de deslaste G tanto \$ara la \$rueba de deslaste de desli&amiento en seco 2 como de abrasi>n a tres cuer\$os se calcula con la ecuaci>n ! , tomada de : arsha I%4M

$$K = \frac{V}{S \cdot N} \quad ! \#$$

donde \ es el volumen removido, 2a sea en la \$rueba de deslaste en seco o abrasi>n a tres cuer\$os, * es la distancia recorrida 2 N es la car1a. Fos ensa2os de adhesi>n/cohesi>n transversal se hicieron si1uiendo el modelo de F>\$e6 I%&M \ encl I% M2 Yu I% MZ uienes anali&aron transversalmente varias muestras de materiales 7abricados \$or \$ro2ecc>n t?rmica mediante el ensa2o de ra2ado transversal. Fos mencionados autores identi7caron dos ti&os de 7allas; adhesiva cuando el tri@1ulo \$ro2ectado est@ en el recubrimiento 2 cohesiva cuando el tri@1ulo \$ro2ectado se encuentra en la inter7a& del recubrimiento 2 el sustrato. = n la medida se utili6> un eAui\$o C*4 Revetest D\$ress*cratch Tester el cual tiene un indentador de diamante ti&o RocJ5 el C, con radio de &' Um. Fos ensa2os se reali&aron con dos car1as constantes, &N 2 %&N, 2 con una velocidad constante de des\$la&amiento de % mm/min. = l @ea doble del tri@1ulo \$ro2ectado se determina mediante la ecuaci>n).

$$A = L_x \times L_y \quad) \#$$

donde A, es el @ea del tri@1ulo F0 2 F2 es la altura del tri@1ulo 2 la base del tri@1ulo res\$ectivamente.

I or Btmo, el \$ar@metro de red se calcul> usando la ecuaci>n \$ara un sistema cubico ecuaci>n 4, 2 se com\$ar> con la relaci>n de Wra11 \$ara 4 =T ecuaci>n &

$$a = d_{hkl} \sqrt{h^2 + k^2 + l^2} \quad 4 \#$$

$$a = \sqrt{\frac{n \lambda^2 L^2}{R^2}} \quad 8 \#$$

siendo a es el \$ar@metro de red, d la distancia inter\$lanar, *, y l son los @ndices de 4 iller, F es la lon1itud de la c@nara del microscopio de transmi>n, R la distancia desde el ha& central hasta el \$unto o anillo di7actado, J es la lon1itud de onda asociada con los electrones Aue es de " , " ! & % , 2 n es la suma de los cuadrados de los @ndices de 4 iller. Fas medidas del es\$esor de los recubrimientos se hicieron con un anali&ador de im@enes.

3.1. Caracterizaci&n morfol&gica

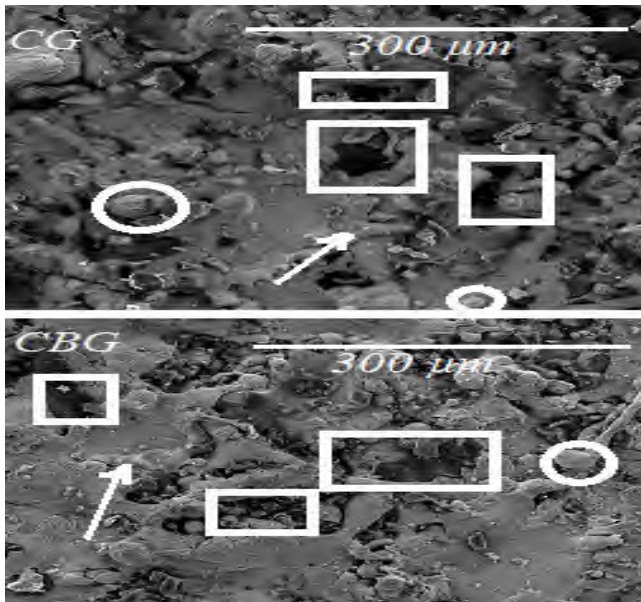
= n la Tabla ! , se resumen los valores de los es\$esores 2 ru1osidades de los recubrimientos 7abricados. Fos valores de ru1osidad del sustrato se deben a la de7ormaci>n \$l@tica a la Aue \$or otra \$arte, el m?todo de \$re\$araci>n mediante disco abrasivo hace un arranAue de viruta 1enerando surcos. = n este estudio se establece Aue la ma2or ru1osidad se obtuvo en los sustratos \$re\$arados con alBmina. =sto es debido a un aumento de surcos \$or de7ormaci>n en el sustrato \$or la alta di7erencia de dure&as Aue e0iste en la aleaci>n de cobre 2 las \$art&ulas de alBmina I% M=stos resultados concuerdan con lo establecido \$or 4 ^Jinen I%&M2 EuJ anuma 2 - hno I% M Auienes han demostrado Aue el m?todo de \$re\$araci>n \$uede a7ectar la ru1osidad 2 \$or lo tanto la adherencia I%&M Fos resultados de la Tabla ! , evidencian Aue los recubrimientos con ca\$a de adherencia tuvieron ma2ores ru1osidades Aue los recubrimientos sin ca\$a de adherencia, esto \$robablemente se debe a Aue los recubrimientos con ca\$a de adherencia se de\$ositaron sobre el sustrato con una ru1osidad modi7cada \$or la ca\$a. I or lo tanto, los Ns\$latQ Aue son \$art&ulas alar1adas Aue se de\$ositan una encima de otra, no se \$ueden 7ormar, lo Aue determina Aue el recubrimiento 7nal ten1a una ma2or ru1osidad.

= n la Ei1. % se muestran micro1ra7as de 4 =W \$ara di7erentes muestras. *e observa Aue las \$art&ulas se es\$arcieron sobre los sustratos en 7orma de ho&uelas.

Tabla ! .
 \alores de ru1osidades 2 es\$esores los recubrimientos \$roducidos.

" uestra	" #todo de Pre\$araci&n	a\$a ad%&rente	Ru&osidad del sustrato '(m)	Ru&osidad del recubrimiento '(m)	* s\$esor recubrimiento '(m)
CI	Disco abrasivo	No	4. % _ ". ! " #	% " , "" _ 3.) 3#	%&'. %& _ ! ") 4#
CW	Disco abrasivo	*i	4. % _ ". ! " #	% " , "" _ %&4) #	! 3" .4" _) . 4) #
CA	S ranallado \$or arena	No	4.44 _ ". ! " #	+ " , "" _ %&.44#	%&".) " _ ! ") 4#
CWA	S ranallado \$or arena	*i	4.44 _ ". ! " #	%&". "" _ %&. & #	! 83.4) _ 3.3" #
CS	S ranallado \$or alBmina	No	+ . & (_ ". 4" #	(3. "" _ %& &4#	% &8. (& _) . %&#
CWS	S ranallado \$or alBmina	*i	+ . & (_ ". 4" #	%&". "" _ %&%84#	! 3&+8 _ 4! .83#

Euente. autores



El 1ura % 4 or 7olo 1(a) del recubrimiento.
Fuente. autores

Adem@ Aue eóisten di7erentes de7ectos mor7ol>ícos, como \$oros se\$alados con rect@íulos 2 \$artículas sin 7undir se\$aladas con cíclos 2 \$or \$ltimo 1rietas se\$aladas con 7echas. =stas 1rietas se deben a la contracci>n de las 1otas al momento de solidi7arse 7ueron sometidos durante el m7odo de \$re\$araci>n de 1ranallado.

3.2. Caracterización química y microestructural

=n la Tabla), se muestra la com\$osici>n Au7nica obtenida \$or ERD de los recubrimientos CS 2 CWS 2 del material en \$olvo. Fos \$orcentajes en \$eso de los elementos \$ermiten establecer Aue el recubrimiento es una aleaci>n de cobre al aluminio, 2 se 1bn 1on5 eiser 11" M el sistema contiene % com\$uestos intermet@ícos, + de ellos s7o son estables a tem\$eraturas elevadas. Al reali7ar una com\$araci>n de la com\$osici>n Au7nica del 1roón !% + % con la de bronce al aluminio comerciales, no se encontraron com\$osiciones similares, 2a Aue el contenido de aluminio sobre\$asa el &X., 2 de acuerdo con Ar\$at 2` r1en 11% M Draissia 2 Debili 11! Mestas aleaciones se com\$onen de tres 7ases de Cu, Al 2 AlCu, me6cladas. Fi 1+ Mestablecen una relaci>n 1ómite de (+.) de las aleaciones de bronce al aluminio. Conclu2endo Aue si esta relaci>n es ma2or, el des1aste es adhesivo \$resentando una 7ase dura PQ2 si esta relaci>n es menor, el des1aste es abrasivo \$resentando una 7ase blanda R. Fos datos de la Tabla) de los recubrimientos \$resentan una 7ase PQ

Tabla).
Com\$osici>n recubrimientos con 2 sin ca\$a de adherencia

" uestra	u	' + wt)	Al	' + wt)	' + wt)	- alance
1olvo	(). (%	)). &X	''''''	1. +4		
CS	+3.8%	%&1.3	1.38	1. +1		
CWS	+''.(!	%&.4	(.3!	1. +1		

Fuente. autores

=n la Ei 1. ! a, se muestran \$atrones de DRD de la muestra en \$olvo 2 de los recubrimientos CS 2 CWS. =n ellos se observan los \$ícos m@ \$redominantes del AlCu), de acuerdo con Fi 11) M=sta 7ase cubica tiene un \$ar@netro de red aa), & [11 4M=stos resultados coinciden con los obtenidos \$or b orlu 2` r1en 11 & M Draissia 2 Debili 11! M

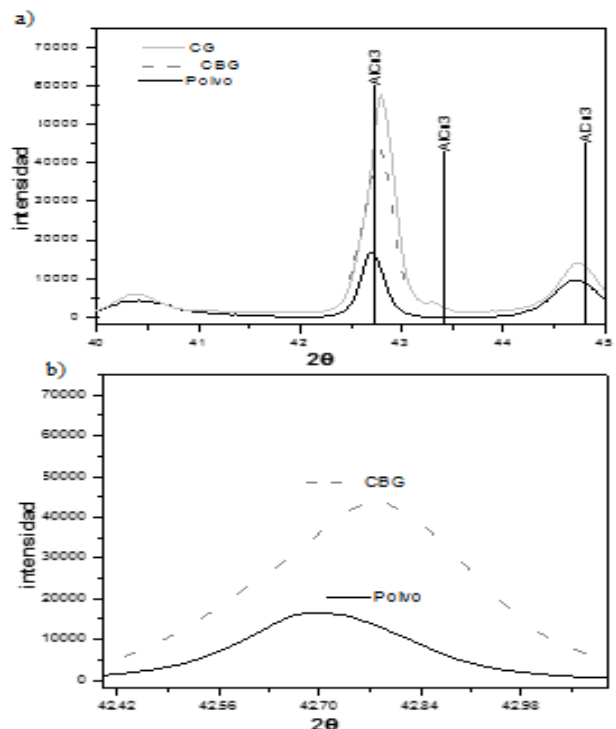
=n la Ei 1. ! b se observa el corrimiento Aue su7ri> el material, en la \$osici>n ! c, (8+V, lue 1o de su \$ro2eccí>n sobre el sustrato. 1ara determinar la de7ormaci>n de la estructura se utili6> la si7uiente ecuaci>n.

$$\varepsilon = \frac{d_n - d_0}{d_0} \times 100 \quad (\#)$$

donde d0 es la distancia inter\$lanar \$ara el material en \$olvo 2 dn es la distancia inter\$lanar \$ara el material \$ro2ectado, si dn > d0 el es7uer6o es \$or tensi>n 2 si dn < d0 el es7uer6o es \$or com\$resi>n. Fos valores obtenidos 7ueron. d0 a !, %&X + [2 dn a !, %&X [2 el \$orcentaje de de7ormaci>n calculado 7ue de ", %&" 4X, resultado Aue indica Aue la de7ormaci>n es \$roducida \$or es7uer6os \$or com\$resi>n 11 (M

3.3. Análisis met

Debido a Aue eóiste una considerable incertidumbre sobre las caracter\$sticas micro' estructurales de estas aleaciones, en \$articular de la distribuci>n de 7ases cristaloi r@cas dentro de la muestra, se \$rocedi> a determinar la estructura cristalina \$resente en los recubrimientos a trav?s de an@lisis de los \$atrones de di7racci>n de electrones 2 de micro1ra7as 4 =T en cam\$eo oscuro de una muestra de \$ositada con ca\$a adherente



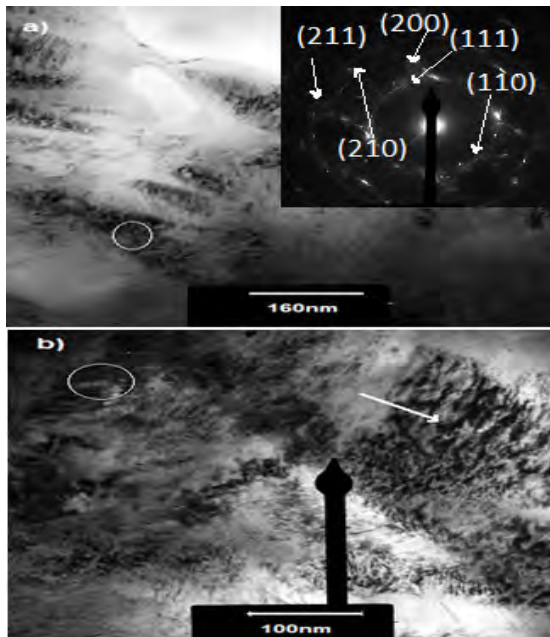
El 1ura !. a# 1 atr>n de di7racci>n de ra2os D \$ara muestra en \$olvo, CS 2 CWS. b# Corrimiento de \$íco en la muestra CWS.

Fuente. autores

Ei1.), 2 una simulaci>n con el so7t5 are I o5 erCell !.4 de la red cristaloi7ica AlCu). I ara la simulaci>n se tomaron los datos de Fi II) Mel cual re\$orta Aue esta estructura \$ertenece al 1ru\$ o e\$acial !!% =n este 1ru\$ o e\$acial los @omos se distribu2en de la si1uiente manera. los iones de Al^f se ubican en las \$untas de la celda 2 los iones de Cu⁺ se ubican en los centros de las caras. =n la Tabla 4, se muestra los valores e0\$erimentales 2 calculados de los \$ar@metros de red 2 los \$lanos asociados. Fa inde0aci>n se reali6> de acuerdo a lo establecido en la literatura II +MFos resultados muestran Aue el \$ar@metro e0\$erimental di7ere del te>rico, se1Bn la ecuaci>n 4 en un %! 3 X 2 se1Bn la ecuaci>n &en un),! 8X. =stos errores est@ dentro del mar1en de \$ermitido.

=n la Ei1.)a, se insert> un \$atr>n de di7racci>n de electrones de @ea seleccionada *A=D#, \$or sus si1las en in1l?s. =n donde se a\$recian los \$lanos asociados de los anillos di7ractados. Fos resultados se muestran en la Tabla 4.

=n la Ei1.)b, se a\$recia la e0istencia de bandas de es7uer6o cortante debido al alto 1rado de de7ormaci>n del recubrimiento; adem@, se observan 6onas de alta densidad de dislocaciones en la estructura se\$alados en c@culos.



Ei1ura). 4 icro1ra7as de 4 =T a# Yonas donde hubo es7uer6os residuales. =n el recuadro se muestra el \$atr>n de di7racci>n de electrones b# Detalles micro estructural de bandas.

Euente. autores

Tabla 4.
alores de los hJl \$ara una muestra \$olicrostalina de AlCu,

h J l	e0\$erimental [#	a sistema cubico [#	a relaci>n de waa1 [#
%6	!.4"(	) .4"	) .)
%86	!.! 33	) .38	) .3"
! ""	%33%	) .38	) .3"
! %	(%) 8+	) .%	) .")
! %6	%! 88	) ."8	) .")!
!! "	%%8&	) .)&	) .! 8
		ga) .48	ga) .4%

Euente. autores

Tabla &
Relaci>n tamao de cristalito dure6a

" uestra	. ama/ o de cristalito 'nm)	0 ure6a	" " Pa)
I olvo	8(.% _3." 8#		% 88
CI	48.8& _! .) 4#		% 3&"" _ (8." 8#
CW	48.! + _8.48#		%83.""" _%6%#
CA	4".3+ _ (.) 4#		%! "" ."" _) 3.) #
CWA	4! .! + _4.4+#		%68.""" _43." 4#
CS	() .48 _3.!! #		%8 (. "" _! 3.3" #
CWS	(! .8(_% .8! #		%)! . "" _43." 4#

Euente. autores

I or Btmo, no se a\$recia un crecimiento de 1rano uni7orme. Fos 1ranos 7nos \$robablemente son resultado de la alta de7ormaci>n \$l@tica. Resultados Aue concuerdan con la investi1aci>n de Goivuluoto I3M

3.4. Propiedades mecánicas

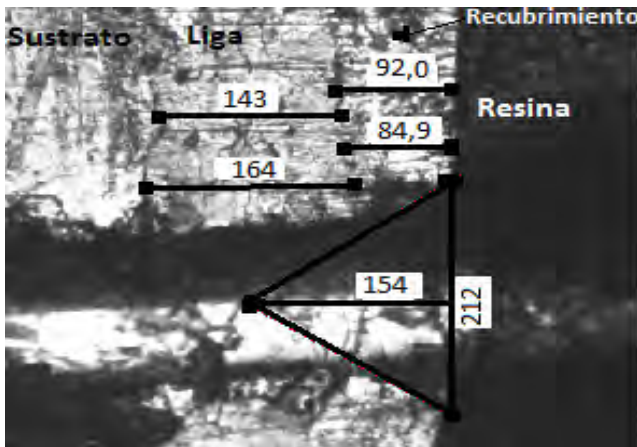
=n la Tabla & se inclu2e la relaci>n de la dure6a con el tamao de cristalito calculada con la 7>rmula de Deb2e' *cherrer. Fa di7erencia entre los tamaos de cristalito de las \$robetas \$re\$aradas con alBmina, 1ranallado con arena 2 con disco abrasivo, se debe al m?todo de \$re\$araci>n, 2a Aue los de\$>itos se hicieron ba8o las mismas condiciones e0\$erimentales. Con res\$ecto a la dure6a se \$udo determinar Aue nin1Bn recubrimiento su\$er> el valor de dure6a del sustrato %6 "8_4% 4 Ia. *in embar1o, el ma2or valor de dure6a 7ue m@ alto Aue el del material en \$olvo. =ste resultado se \$uede e0\$licar considerando los es7uer6os residuales a com\$resi>n Aue se 1eneraron en el momento del de\$>ito. Adem@, los resultados indican Aue los recubrimientos con ca\$a de adherencia \$resentaron ma2or dure6a Aue los sin esta ca\$a.

I or Btmo, los recubrimientos \$re\$arados con 1ranallado con arena \$resentaron una relaci>n : all'I ech, es decir a ma2or tamao de cristalito ma2or dure6a. Fos recubrimientos \$re\$arados con disco abrasivo tienen \$r@ticamente los mismos tamaos de cristalito, lo Aue im\$lica Aue no se \$uede determinar la relaci>n de : all'I ech II 3M

3. . Pruea de ad"erencia

Fas \$ruebas de adherencia se reali6aron de acuerdo al m?todo descrito en la secci>n !. =n la Ei1. 4, se \$uede observar un tri@1ulo obtenido en la \$robeta CWA con una car1a de %&N. *e identi7ica Aue el tri@1ulo se encuentra dentro del recubrimiento. =l @ea se calcul> con la ecuaci>n). =n esta 71lura, tambi?n se \$ueden observar los es\$esores de las ca\$as del recubrimiento.

=n la Tabla (, se consi1nan los resultados de la \$rueba de adhesi>n/cohesi>n. Fos valores obtenidos \$ermiten establecer Aue el recubrimiento CS tiene valores similares con las dos car1as. Adem@, la car1a de %&N \$resent> menor @ea \$ro2ectada. Tambi?n se \$resentan valores Aue indican Aue todos los recubrimientos 7allaron \$or cohesi>n debido a Aue los tri@1ulos se obtuvieron en la su\$erficie de los mismos, de manera Aue en este ensa2o el recubrimiento CS 7ue el Aue \$resent> menor 7alla \$or cohesi>n. =n cuanto a los sustratos tratados con \$ulidura se des\$rendieron sin hacer



Ei 1ura 4. T ruebas de adherencia, donde se muestra el tri@tulo \$ro2ectado \$robeta CWA con %&N medidas en micras.
Eiente. autores

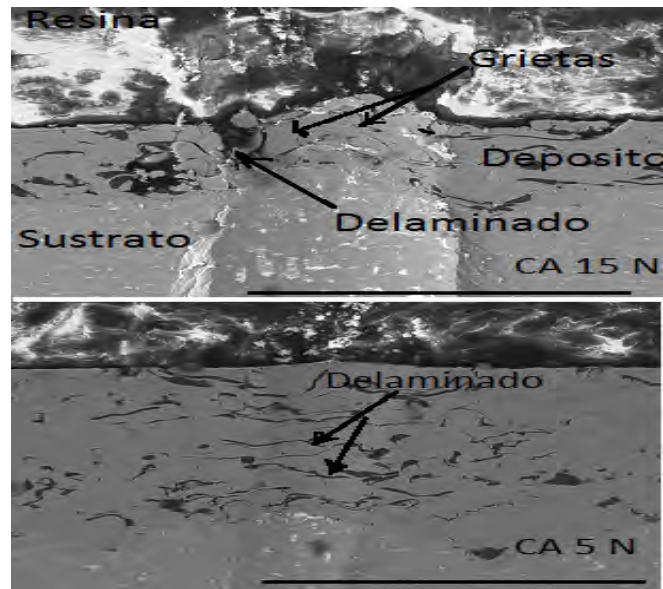
Tabla (.
Datos del ensa2o de la \$rueba de adherencia transversal

" uestra	ar &a '1)	2 rea '(m ²)	. i\$o de \$alla
CA	&	%& 84 _ %& #	Cohesiva
CA	%&	) 3+83 _ 88" #	Cohesiva
CWA	&	%& (" " _ (8" #	Cohesiva
CWA	%&	) 8! 4% _ 3) + #	Cohesiva
CS	&	! 8" 4+ _ ! 3" #	Cohesiva
CS	%&	! 3+ %& _ 4) & #	Cohesiva
CWS	&	! (! % _ ! 8" #	Cohesiva
CWS	%&	(%& 8+ _ 38" #	Cohesiva
CWI	&	%& 44%	Cohesiva
CWI	%&	) + & 4%	Cohesiva

Eiente. autores

es 7uer6o mec@ico, \$or esta ra6>n, solo se \$udo hacer una toma de datos a los recubrimientos CWA. =stos resultados est@ de acuerdo con las investi1aciones de 9 an1 I% M2 de 4 ellali I% M Aue determinaron Aue la adherencia se ve a7ectada con la ru1osidad del sustrato lle1ando a concluir Aue con una ma2or ru1osidad se me2ora la adherencia debido a Aue se \$roduce ma2or su\$er7icie de anclaje. T ara determinar los mecanismos de 7alla en el ensa2o de adherencia \$or ra2ado transversal 2/o corroborar la 7alla cohesiva, ha2 Aue observar microsc>ticamente el tama2o de las 1rietas.

=n la Ei1. & se muestran las im@enes 4 =Wde las huellas de2adas en dos \$robetas, una con la car1a de %&N 2 la otra con la car1a de &N. *in embar1o, como los recubrimientos tuvieron es\$esores h) &' micras, sur1i> una 1rieta en la inter7a6 sustrato/recubrimiento con la car1a de %&N. =n estos casos, tanto la adhesi>n 2 la cohesi>n se caracterizaron aunAue s>lo la cohesi>n \$odr@ ser cuantificada mediante el c@culo del @ea del tri@tulo. Fas 1rietas indican Aue estos recubrimientos se delaminan en condiciones severas de traba2; adem@ se observa Aue ha2 un 7u2o \$l@tico Aue est@ de acuerdo con la investi1aci>n de =ric7so U 3M Aue determinaron Aue los recubrimientos m@ blandos e0hiben de7ormaciones \$l@ticas, 2 los m@ duros tienen des1aste \$or abrasi>n con de7ormaci>n \$l@tica, lo Aue \$roduce 7ractura.



Ei 1ura & : uellas del des1aste \$or el ra2ado =scala) " " "Um.
Eiente. autores

3.#. Prue! as de desgaste por a! rasi3n a tres cuerpos

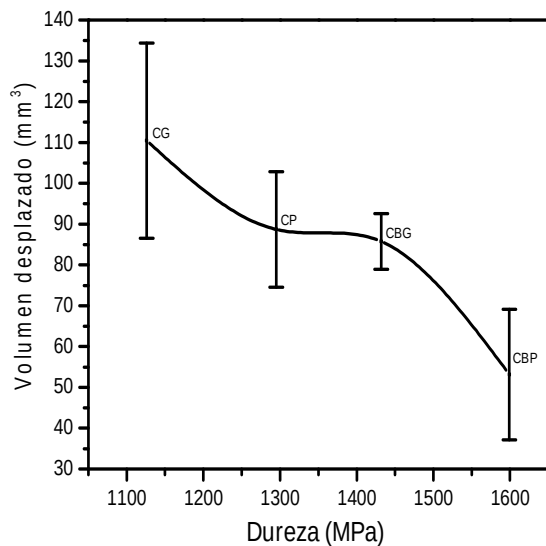
=n este ensa2o se midi> la tasa de des1aste del sustrato \$ara tener valores de com\$araci>n con los resultados de los recubrimientos. =n la Tabla +, se muestra el volumen des\$la6ado calculado, 2 la tasa de des1aste \$ara esta \$rueba. =ste ensa2o se hi6o con las \$robetas \$re\$aradas con disco abrasivo 2 \$or 1 ranallado \$or alBmina, esto es debido a Aue los m?todos de \$re\$araci>n \$or 1 ranallado con arena 2 disco abrasivo \$resentaron la misma ru1osidad. Fos valores de la Tabla + indican Aue, en todos los recubrimientos de\$ositados con 2 sin ca\$a de adherencia, el @ndice de des1aste 7ue menor Aue el del sustrato.

T ara relacionar la dure6a con el volumen des\$la6ado, se si1ui> la metodolo1@a de Ean1 D) "M2 \$ore D) %M Auienes tra6aron una 1r@tca con los datos de dure6a en el e0e 0 2 los de volumen des\$la6ado en el e0e 2. Cuando ha2 una alta contribuci>n de des1aste abrasivo la curva muestra una 7orma de * variando con la dure6a 2 cuando no \$resenta esta 7orma el mecanismo de des1aste \$resente es adhesivo. =n la Ei1. (, se muestra la 1r@tca donde se relaciona la dure6a contra el volumen des\$la6ado. Fa Ei1. (no \$resenta 7orma de *, \$or lo tanto, el mecanismo de des1aste 7ue adhesivo. Adem@, \$ara corroborar este resultado se tomaron micro1ra7as 4 =W 2 se analizaron las 6onas donde se \$resent> des1aste abrasivo 2 des1aste adhesivo.

Tabla +.
\ olumen e @ndice de des1aste \$rueba de abrasi>n a tres cuer\$os

4 uestra	\ olumen des\$la6ado mm ³ #	G %'+ mm ³ N' "mm ³ #
*ustrato	%& (,3(_ %& +4#	%
CI	88,+" _ %& ,% #	4,+
CWI	89, %& _ %& , " ! #	! ,8
CWS	88,++ _ (,8! #	4,&
CS	%& ,48 _ !) ,88#	&3

Eiente. autores

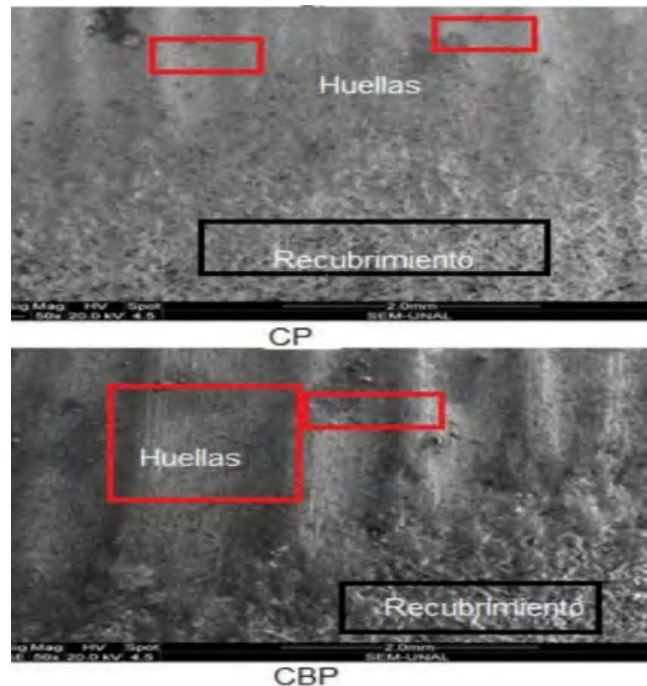


Ei1ura (. S ra7ica de Dure6a contra volumen des6a6ado
Fuente: autores

=n la Ei1. +, se muestran las micro1ra7as de las huellas de este ensa2o. Fos recuadros ro8os se6alan la distancia entre los surcos de las huellas, 2 los recuadros ne1ros se6alan la del recubrimiento. *e a6recia Aue las distancias entre las huellas no cambian si ni7cativamente, 2 de acuerdo a la Ei1. + 2 la Tabla +, e0iste un cambio entre el volumen des6a6ado 6ero no en la distancia de las huellas del ensa2o. De manera Aue el mecanismo de des1aste, 6ara este ensa2o 7ue 6or de7ormaci>n 6l@tica. Fa de7ormaci>n 6l@tica se debe a la dure6a 2 a la estructura cristalina de los recubrimientos 2a Aue la dure6a de un material indica el 6orcenta6e de de7ormaci>n 6l@tica Aue tienen los materiales 2 la estructura cristalina determina el sistema de des6amamiento D) %M=n este estudio los recubrimientos 6resentaron ba6os valores de dure6a 2 una estructura ECC, la cual tiene % sistemas de des6amamiento. Adem@, teniendo en cuenta lo e06uesto en la secci>n de DRD, este recubrimiento 6resenta una 7ase PQ

3.6. Prue6as de desgaste por deslizamiento

=n la Ei1. 8, se muestran las micro1ra7as 4 =Wde las huellas del des1aste de los recubrimientos de 6ro2ectados con 2 sin ca6a li1a. *e a6recia Aue e0isten re6iones de color 6ris oscuro resaltados en recuadros a6ules. Y de acuerdo a =dris2 D) ! M Auienes determinaron los mecanismos de des1aste 6ara la 6rueba de N in' on' DisJ Q indicaron Aue encontraron 6onas con la misma tonalidad de 6ris oscuro, donde se 6resent> un mecanismo 6or o0idaci>n, 6ara esta 6rueba. 6ara saber 6or Au? e0iste este ti6o de mecanismo de des1aste 4 ohant2 D)) M describieron Aue el coe7iciente de 7ricci>n C- E# e0hibe una 7uerte de6endencia con la velocidad de des6amamiento, 6ara recubrimientos hechos con 6ro2ecc>n t6rmica, ca2endo el C- E cuando la velocidad aumenta. Y aclaran Aue 6osiblemente esto es causado 6or una combinaci>n de calentamiento local Aue disminu2e la resistencia a la ci6alladura su6er7icie del recubrimiento 2 a la 7ormaci>n

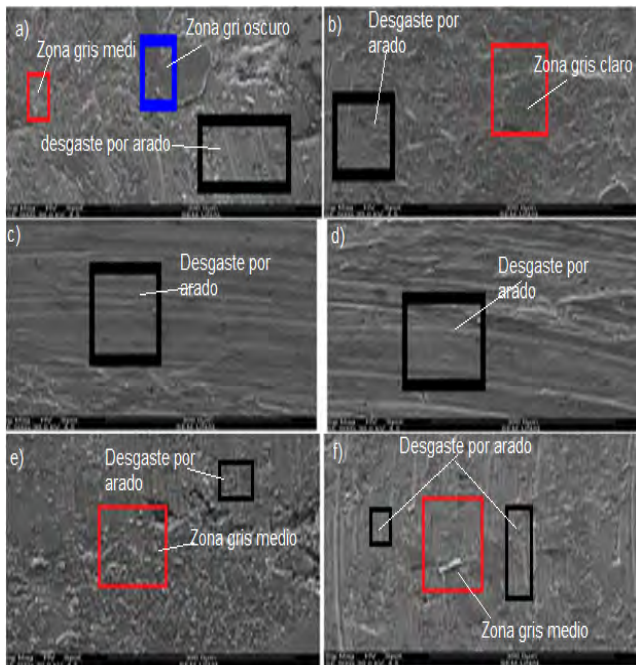


Ei1ura +. 4 icro1ra7as 4 =Wde las huellas de6adas en la 6rueba de abrasi>n en los recubrimientos CWI 2 CI =scala. ! mm.
Fuente: autores

de 6el6ulas de >0ido, debido a las tem6eraturas altas de contacto. De modo Aue, las 6onas Aue 6resentaron esta tonalidad de 6ris oscuro en los recubrimientos 6osiblemente se deban a un mecanismo de des1aste 6or o0idaci>n. 6ara6almente se a6recia la e0istencia de re6iones con un color 6ris medio Aue se se6alan con los recuadros ro8os. =n estas 6onas los N6latsO se a6lanan como resultado de la de7ormaci>n 6l@tica durante el uso 2 se e0tru2en en la direcci>n de des6amamiento, lo cual tambi>n lo re6ortaron 4 ohant2 D)) M2 =dris2 D) ! M Auienes tambi>n indicaron Aue la de7ormaci>n 6l@tica conlleva a un des1aste adhesivo. Fas 6ro6etas Aue 6resentaron este mecanismo de des1aste en ma2or son CS, CWA 2 CW5. =l otro mecanismo de des1aste Aue se 6resent> en esta 6rueba 7ue la abrasi>n 6or arado, Aue se denota con los recuadros ne1ros. =sto se debe a Aue el recubrimiento des6rende 6art6ulas las cuales no se remueven 2 Auedan embebidas en el recubrimiento, 6enerando a6Cun des1aste abrasivo a tres cuer6os. *e a6recia Aue las 6onas donde e0isti> este ti6o de des1aste se 6eneraron huellas en 7orma de canales, tales como las de un tractor cuando ara la tierra. =sto est@de acurdo con la investi1aci>n hecha 6or Yuan2uan D) 4MFas 6ro6etas Aue 6resentaron este ti6o de mecanismo de des1aste son CA, CI, CWI 2 WS.

=l mecanismo de des1aste Aue se 6resent> con ma2or re6ularidad 7ue el arado. =sto se debe a Aue la dure6a de la es7era usada 6ara la 6rueba es de (&Rc, al ser m@ duro Aue el recubrimiento este lo des6rende 6enerando virutas del mismo recubrimiento Aue se com6ortan como un medio abrasivo, 6enerando abrasi>n a tres cuer6os.

=n la Tabla 8, se inde0an los resultados del ensa2o de N6in on DisJ O como el ancho de huella volumen removido, el coe7iciente de des1aste 2 el de 7ricci>n. *e 6uede observar



El 1ura 8. 4 icro1ra7as 4 =Wensa2o de N in on' DiscOa) ""Um a#CA b# CWA c#CI d#CWI e#CS 7#CWS .
Fuente. autores

Tabla 8.
Resultado ensa2o N in on DisO

" uestra	b ' (m)	4 'mm ³	5 10 ⁶ 'mm ³ 1 ⁶ 'mm ⁶	oe3iciente de 3ricci3n
*ustrato	(+ ". (+ _ (.38# %8+ _ ". "(#	(. (& _ ".1+ #	". %8 _ ". "(#	
CI	+ (4. (+ _ %3. (4# !.13 _ ". %8#	%6! _ ". +8#	". %88 _ ". "(#	
CWI	+ (! &) _ ". .34# !. %8 _ ". "(#	3. ! _ %88#	". %88 _ ". "(#	
CA	8. % (+ _ 48.88# !. 8& _ ". .38#	%8.8 _ 4. % #	". %6 (_ ". "(#	
CWA	% " + (+ _ +.88# 8.) + _ ". ! 8#	)) .3 _ % "(#	". !) 3 _ ". %8#	
CS	+33. " " _ %834# !. +! _ ". ! 8#	% 4 _ % "(#	". %8 _ ". " 88#	
CWS	(8+ (+ _ !. !. 84# %3& _ ". !. ! #	+ .44 _ ". .3#	". %8+ _ ". " 4#	

Fuente. autores

Aue el 3ndice des1aste 7ue ma2or en la \$robeta CWA. Fo Aue indica Aue \$ara esta \$robeta el volumen removido 7ue ma2or los recubrimientos Aue \$resentaron valores \$r3ticamente i1uales del C- E 7ueron CWS , CI 2 CWI , 2 la muestra Aue \$resento menor 3ndice de des1aste 7ue la \$robeta CWS . Como el valor del 3ndice de des1aste 7ue menor en las muestras \$re\$aradas \$or 1ranallado met3ico, este m?todo de \$re\$araci3n a2uda a reducir el 3ndice de des1aste. Como la ru1osidad del recubrimiento se cambi3 debido a Aue se \$ulieron las muestras antes del ensa2o con una li3a ("" \$ara hacer el ensa2o de N in on DisJ Q no se \$uede relacionar los datos de la ru1osidad del recubrimiento con el C- E 2 el 3ndice de des1aste. No e3isti3 una relaci3n entre la dureza 2 el 3ndice de des1aste. I3r 3ltimo, la di3ferencia entre los resultados se debe a los mecanismos de des1aste Aue se \$resentaron.

8. onclusiones

=n este trabajo se lo1raron de\$ositar recubrimientos de Cu₃Al₂ mediante la t3cnica de \$ro2ecci3n t3rmica sobre

sustratos de lat3n, con \$re\$araci3n su\$erficial a trav3s de tres t3cnicas. disco abrasivo, 1ranallado \$or arena 2 1ranallado met3ico, de\$ositados con 2 sin ca\$a adherente. Fos resultados obtenidos \$ermiten concluir Aue.

% 4 ediante los ensa2os de 4 =T 2 DRD se \$udo establecer Aue la 7ase cristal3rica de los recubrimientos es AlCu₃.

!. Fos recubrimientos con ca\$a adhesiva \$resentaron los ma2ores valores de dureza. =n el ensa2o de adhesi3n/cohesi3n todas las muestras 7allaron \$or cohesi3n 2 se determin3 un 7u3bo \$l3tico.

). =l ensa2o de abrasi3n a tres cuer\$os mostro Aue los recubrimientos con 2 sin ca\$a adhesiva tienen menor 3ndice de des1aste Aue el del sustrato.

4. =l ensa2o de N in on DisJ Q Aue mide el 3ndice de des1aste \$or desli3amiento, determino Aue es ma2or en los recubrimientos Aue en el sustrato.

& =l ensa2o de N in on DisJ O determino Aue los mecanismos de des1aste Aue se \$roducen en los recubrimientos son. o3idaci3n, \$l3tico 2 arado.

(. =l \$ar3metro de adhesi3n/cohesi3n 3ndico Aue el recubrimiento denominado CS \$otencialmente \$uede ser a\$licado en la recu\$araci3n de \$ie6as, 2a Aue \$resenta un ba3o 3ndice de des1aste en el ensa2o a tres cuer\$os.

A3radecimientos

Fos autores de este trabajo e3o\$resan su a1radecimiento a Colciencias \$or el a\$3o2o o7recido mediante el \$ro2ecto ! " % % " % & (" a Cotecmar \$or el a\$3o2o t3cnico 2 a I3 ro2met Ft3da \$or \$restar las instalaciones \$ara hacer los recubrimientos.

Re3erencias

- I3M I3rchliJ, F., *am\$ath, *, S3tleber, ;., Wanc3e, S. and Ru77, A.9 ., E3riction and 5 ear \$ro\$erties o7 9 C'Co and 4 o'4 o' C based 7unctional12 graded materials. 9 ear, ! 43 % # \$\$. %%) ' %88& ! " " % D- ., % . % % / * " " 4) ' (48 " % # " 8) 3 " "
- I3M Wau, I. ;. and Rid1e, - ., A*4 : andbo3 mechanical testin1 and evaluation =. UU, A*4 , 8, \$\$. (% 3) 3, ! " " " .
- I3M Son3ale6, R., Cadenas, 4 ., Eernande6, R., Corti6o, ;.F. and Rodri1ue6, =., 9 ear behaviour o7 7lame \$3ra2ed NiCrW'i coatin1 remelted b2 7lame or b2 laser. 9 ear, ! (!) ' 4 #, \$\$.) " %) " +, ! " " +. D- ., % . % % / 85 ear. ! " " (" & " " 3.
- I4M Co\$3er Develo\$ment Associ3n. Ien I3neaMj Consuldata el ! 4 ' % ' ! " % MDi\$3nible en. 5 5 5 . co\$3erin7o.co.w7/al1o2s/bron6e
- I8M borlu, W and ` r1en, 4 ., 4 odifi3cation o7 co\$3er surfaces 5 ith cathodic arc aluminum \$lasma. *ur7. < Coat. Tech., ! " & ! # \$\$. 84 " " 844, ! " % . D- ., % . % % / 8sur7coat. ! " % . " +.) 4
- I3M E3ron, D., Corrosion behaviour and \$rotection o7 co\$3er and aluminum al1o2s in sea5 ater. 9 oodhead. %3a ed. Corn5 all, =n1lan, ! " " +, \$\$. % + % 4 " .
- I3M Fi, Y., Feo, T. and Dia, 9 ., 4 echanical, 7riction and 5 ear behaviors o7 a novel hi3h stren1th 5 ear resistin1 aluminum bron6e. 9 ear, %3+ % ! # \$\$. % " " % 3 (, %33 (. D- ., " . % % / " " 4) ' % 48 38# (83 " " !.
- I8M 9 illiams, D.W and =din1ton, ;.9 ., 4 icrostructural characteristics o7 \$3lat' Auenched aluminium' co\$3er al1o2. ;. - 74 ate. *ci. % # \$\$. % (' %) , %3+ (. D- ., % . % % " + / W E " " " +) 84 + +
- I3M Goivuluto, : ., : onJanen, 4 . and \ uoristo, I., Cold' \$3ra2ed coo\$3er and tanatulum coatin1s' Detailed E= =4 and T=4 anal2sis. *ur7. < Coat. Tech., ! " 4 % 8 # \$\$. % . !) & !) (% ! " % . D- ., % . % % / 8sur7coat. ! " % . " % " " %
- I3M : inca\$ie, 9 .*, - la2a, ;. ;. 2 Al7onso, ;. =., I3ro\$iedades tribol3gicas de recubrimientos de Cr0- 2 de\$ositados mediante \$ro2ecci3n

Cooperation strategies featuring optimization in the school transportation system in Bogota

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Abstract

The transport of students presents important challenges in the case of the city of Bogota, where an important cluster of schools is located in one zone, but there is only one road connecting these schools to residential zones. Thus, traffic congestion is high, generating long travel times for students, high operational costs, and mobility problems. This paper studies the impacts of a cooperative strategy between logistics operators using a mixed integer programming mathematical model, to find the optimal design of school routes on a network with the topology that describes the aforementioned road system. Two strategies are compared: a mixed loads strategy, where students from different schools share buses; and a single load strategy, where students from different schools cannot share buses. The objective is to minimize the total operational costs while satisfying the schools' time windows. Comparative results of the two models using exact and heuristic approaches are presented.

Keywords: school bus routing; routing and scheduling; heuristics; traffic congestion; mathematical models.

Estrategias de cooperación en el sistema de transporte de estudiantes en Bogotá usando optimización

Resumen

El transporte de estudiantes tiene desafíos importantes en el caso de la ciudad de Bogotá, donde un grupo de escuelas se encuentra en una zona, pero sólo hay una carretera que las conecta con zonas residenciales. Por lo tanto, la congestión del tráfico es alta, generando largos tiempos de viaje, altos costos de operación y problemas de movilidad. Se estudia el impacto de una estrategia cooperativa entre operadores logísticos a través de modelos de programación de entera mixta, para encontrar el diseño óptimo de rutas escolares en una red con la topología que describe el mencionado sistema vial. Se comparan dos estrategias: Cargas mixtas y carga única, donde los estudiantes de diferentes escuelas comparten o no los autobuses disponibles. El objetivo es minimizar los costos totales de operación respetando las ventanas de tiempo de las escuelas. Se presentan los resultados comparativos de los modelos usando enfoques exactos y heurísticos.

Palabras clave: ruteo de buses escolares; ruteo y secuenciación; heurísticas; congestión vehicular, modelos matemáticos.

1. Introduction

Cities have the challenge of defining a sustainable urban mobility model to improve the population's quality of life [1]. High traffic congestion levels tend to increase despite infrastructure investments as a result of the rise in the number of vehicles [2]. This congestion generates low productivity,

and pollution.

School buses are part of transportation systems and contribute to traffic congestion, since these buses transport students during rush hours. Thus, an interest to study the school bus routing problem (SBRP) arises. The problem is first studied by [3] who propose to design a schedule for a fleet of school vehicles to pick up students at different geographic points and

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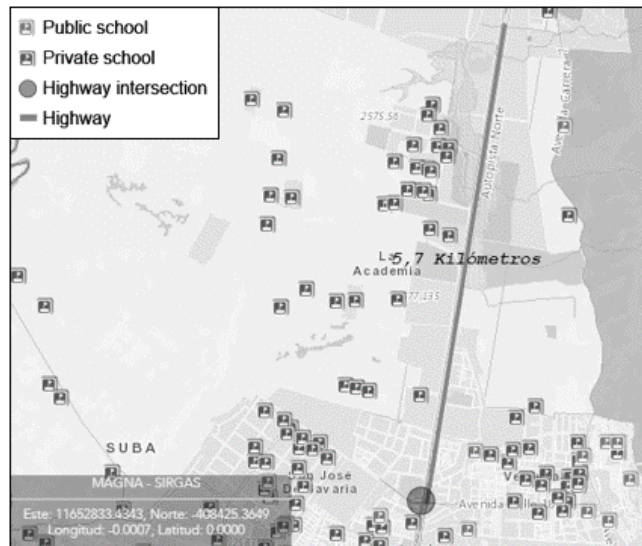


Figure 1. Map of the north of Bogotá – School zone.
Source: <http://mapas.bogota.gov.co/?webmap=1bca24092fc447cfb94177305a272a2e&widgettoopen=Legend>

deliver them to their designated schools, while respecting the maximum capacity of students in a bus, the maximum time travel, and the time window that students have to arrive to class. Different variants have been studied, such as considering a heterogeneous fleet of buses; multiple school systems in rural or urban zones; different planning horizons (morning, afternoon, or both); or special-education students (e.g., students with disabilities). Different objectives are sought, such as: the reduction of the number of buses; travel times; and the minimization of the distance that students have to walk to bus pick-up points (see [4]).

In the case of Bogotá, Colombia, and the highway called *Autopista Norte*, a high level of traffic is found on the *Autopista Norte* during rush hours, since this is the only road that links the northern school zone to residential zones (see Fig. 1). The problem is the increased travel times that students spend on the bus. Further, according to the INRIX Global Traffic Scorecard, Bogotá was the fifth-worst city in the world in terms of traffic severity in 2016.

This problem has been analyzed by the district government. In 2017, the District Department of Mobility [5] restricted a lane to be used exclusively by school buses in rush hours. Results show that average travel times on the highway have been reduced from 43 to 23 minutes. Despite these measures, traffic congestion in the city remains a problem.

Case studies on this issue have been presented. For instance, in Beijing, congestion and pollution consequences of driving-to-school trips were analyzed by [6]. For Dublin, a study of sustainable school commuting was done by [7] and in US the cost of school transportation was analyzed [8].

This paper studies the impact of collaborative strategies for student transportation in the north of the city of Bogotá, through the use of optimization models. The transportation system is analyzed considering independent routes. This strategy is known as “Single load” [9]; it consists of designing routes to pick up students who attend a single

school. The shared routes strategy; known as “Mixed load”, is also analyzed, where students from different schools share buses [10].

The mixed load strategy offers better coordination in highway sequencing, since a collaborative planning of routes for different schools is feasible. The single load strategy presents some issues: entry to the highway can only be coordinated for buses going to the same school, but buses from different schools will get on to the highway in an uncoordinated way. The collaborative strategy has potential benefits such as shorter routes (less travel time); less operating costs (less buses); greener operation (less fuel consumption); and reduced traffic congestion.

The main contribution of the paper is the analysis of the benefits and implications of both strategies, and the conclusions as to the most efficient route design for the school transportation system in the city. A routing and scheduling model is presented to perform this analysis. This paper is organized as follows: section 2 presents a literature review; section 3 presents the proposed mathematical formulation; section 4 presents a proposed heuristic approach; section 5 shows computational results; and section 6 presents the conclusions and future research.

2. State of the art

This section presents a review of the literature related to the school bus routing problem. Notions referring to vehicle scheduling are presented to contextualize the school bus routing problem. The objective of SBRP is to plan an efficient schedule for a fleet of school buses to pick up students at different geographic points and deliver them to the designated school [4]. The SBRP is a particular application of the vehicle routing problem (VRP). In the latter problem, several clients are visited by a set of vehicles, which leave a depot, visit the clients, and return to the depot after completing the route [11]. One variant of the classical VRP, that is similar to the SBRP, as presented in this research, is the multi-depot open vehicle routing problem (MDOVRP), which is studied by [12]. The MDOVRP considers the vehicles to start their journeys from multiple depots to deliver products to clients. When vehicles complete the journey, it is not necessary to return to the depot where the route started [13]. Compared to SBRP, depots correspond to the points where buses start their routes; clients that have to be visited correspond to students who have to be included on different routes; and the designated school in which buses complete the route correspond to the last client in the route. In some European and North American countries, students are collected at fixed points (often clusters of houses or neighborhoods). Nonetheless, in Bogotá, students must be picked up right outside their houses.

The SBRP is known to be NP-Hard [14]. A mathematical model to optimize school bus service of two schools is proposed in [15]; the model is solved by an exact method. Recently, models in the literature have aimed to minimize the transportation costs associated with travel time. A rural school district SBRP using heuristics is proposed in [16]. Similarly, [17] propose an ant colony optimization algorithm. Mathematical models to determine the routes of each bus,

and the stations where students have to walk to be picked up is developed in [18]. A particle swarm optimization to solve the SBRP is proposed in [19].

At the national level, the SBRP has already been applied to a private school in the city of Bogota by [20]. They modeled the system as a capacitated vehicle routing problem (CVRP) and solved it in two phases: the first stage assigns students to buses, and the second determine the vehicle routes via an ant colony optimization. The total distance covered by buses is reduced by 8,3% in the morning. However, this research does not take traffic congestion into account.

Further, the mixed load strategy for the SBRP has been studied by [21], who developed an algorithm to improve the results obtained in [10]. The implementation of the mixed load to a single load strategy is compared in [22]. In contrast to previous research, we will include the bus scheduling decisions at the node that represents the path along the highway that connects schools to students' houses.

Additionally, [23] studied the vehicle routing and scheduling in a cross-docking system. In this research, school buses are scheduled at the node that represents the highway, an analogy of the cross-docking system for a single bus dock is implemented here, where the vehicle entry is scheduled while it is unloaded and delivered from the station [24].

The conclusion of this review is that there is no—

to the best of our knowledge—paper that simultaneously combines the routing and scheduling decisions of buses in a school routing system of single and mixed load strategies where vehicles have to tackle heavy traffic congestion on highways to transport students to their designated schools. Moreover, the impact of each of the two strategies for school route transportation will be analyzed for the studied case.

3. Mathematical formulations

In this section, the mathematical formulations based on mixed integer programming (MIP) for the single load and mixed load strategies are presented. We assume that students have no special requirements other than being picked up at their homes. The fleet of buses is homogeneous and the transfer of students between buses is not allowed. Thus, the bus that picks up each student is the same bus that delivers the student to his/her school.

3.1. Mathematical formulation for school bus routing and scheduling problem – single load strategy

Let the problem be mathematically defined on a directed graph $G = \{v, e\}$. The set $v: \{\theta_k\} \cup \{j\} \cup \{a\} \cup \{m\}$, where $\theta_k < j < a < m$. That is, the set of nodes v is composed by a set θ_k of bases where buses are located at the beginning of the journey, the set j represents the students to pick up. The total number of students in the system is denoted by the constant C . The vertex a represents the *Autopista Norte* highway, and the vertex m represents the destination school. We assume that set k denotes the set of available buses, each with a maximum capacity of Q students, and a fixed cost of used of Cf . Let set $v1$ be a copy of set v ; set $j1$ be a copy of set j ; and set $k1$ a copy of set k .

Set j is associated with a parameter d_j to indicate the number of students to collect at each node and the service time s_j at node

j . The school is associated with parameters w_1, w_2 , indicating the earliest and latest times, respectively, that the students are expected to arrive at school.

The set of edges e in the graph represent the roads in the city of Bogota. Using a geographical information system, the parameter $ti_{(v,v1)}$ representing the travel time from node v to node $v1$ in set V is computed. The variable cost of the bus operation, denoted as $Cv_{(v,v1)} \forall (v, v1)$, is calculated with the expression: $(D_{(v,v1)} * Cud)$, where $D_{(v,v1)}$ refers to the distance between the nodes v and $v1$, a parameter that is calculated with the following expression $(ti_{(v,v1)} * V)$, where V is a constant that represents average bus speed. Additionally, the parameter Cud is a constant that refers to the cost per unit of distance. Further, let R denote the desired minimum time difference between two consecutive bus arrivals to the highway. The bigger the parameter R , the less likely it is that buses will create a bunching effect.

The decision variables in this model are the following: Let $X_{v,v1,k}$ be equal to 1 if the bus k uses edge $(v, v1)$, otherwise it is equal to 0. Let $Y_{k,k1}$ be 1 if bus k precedes bus $k1$ in the sequence to pass along the highway, otherwise let it be 0. Let $L_{v,k}$ be the cumulative number of students in bus k after visiting node $v \in V$. Let $T1_{v,k}$ be the arrival time of bus k at node v , only defined at nodes in the set k and j (points where the routes start and the children houses.) Let $T2_{a,k}$ be the arrival time of bus k at node a . Let $T3_{a,k}$ be the leaving time of bus k at node a . Finally, let $T4_{m,k}$ be the arrival time of bus k to node m . The objective function (1) of the model is to minimize the total cost of the operation of the fleet of buses, which is in function of the route variable cost (Cv) and the fixed cost (Cf) of the operation of each bus, explained above.

$$\text{Min } Z = \sum_k \sum_j Cf * X_{\theta_k,j,k} + \sum_v \sum_{v1} \sum_k Cv_{(v,v1)} * X_{v,v1,k} \quad (1)$$

Subject to:

$$X_{v,\theta_k,k1} = 0; \forall v, \forall k, \forall k1 \quad (2)$$

$$X_{a,j,k} = 0; \forall j, \forall k \quad (3)$$

$$\sum_k X_{v,v,k} = 0; \forall v \quad (4)$$

$$\sum_v \sum_{k1} X_{\theta_k,v,k1} = 0; \forall k \neq k1 \quad (5)$$

$$\sum_v X_{m,v,k} = 0; \forall m, \forall k \quad (6)$$

$$Y_{k,k} = 0, \forall k \quad (7)$$

The first group of constraints indicate which routes do not exist. Eq. (2) guarantees that no starting point will be visited after starting the route. Expression (3) forbids that buses pick up students after having visited node a (highway). Eq. (4) forbids that buses leave a node and return to it consecutively. Eq. (5) forces buses to avoid starting a route from another bus's base. Expression (6) guarantees that the routes finish when the bus arrives to school. Finally, eq. (7) avoids the scenario in which k precedes itself.

$$\sum_v \sum_k X_{v,j,k} = 1; \forall j \quad (8) \quad T1_{j,k} + s(j) + ti(j, a) \leq T2_{a,k} + w_2 * (1 - X_{j,a,k}); \quad \forall j, \forall k \quad (22)$$

$$\sum_v X_{v,j,k} = \sum_v X_{j,v,k}; \forall j, \forall k \quad (9) \quad T1_{j,k} + (s(j) + ti(j, a)) * X_{j,a,k} \geq T2_{a,k} - w_2 * (1 - X_{j,a,k}); \quad \forall j, \forall k \quad (23)$$

$$\sum_v X_{v,a,k} = \sum_v X_{a,v,k}; \forall k \quad (10) \quad T2_{a,k} + s(a) \leq T3_{a,k} + w_2 * (1 - X_{j,a,k}); \quad \forall j, \forall k \quad (24)$$

$$\sum_j X_{\theta_k,j,k} \leq 1; \forall k \quad (11) \quad T2_{a,k} + s(a) * X_{j,a,k} \geq T3_{a,k} - w_2 * (1 - X_{j,a,k}); \quad \forall j, \forall k \quad (25)$$

$$X_{v,v1,k} \leq \sum_j X_{k,j,k}; \forall k, \forall v, \forall v1, v \neq v1 \quad (12) \quad T3_{a,k} + ti(a, m) \leq T4_{m,k} + w_2 * (1 - X_{a,m,k}); \quad \forall m, \forall k \quad (26)$$

$$\sum_j X_{\theta_k,j,k} \leq \sum_{j1} X_{j1,a,k}; \forall k \quad (13) \quad T3_{a,k} + (ti(a, m) * X_{a,m,k}) \geq T4_{m,k}; \forall m, \forall a, \forall k \quad (27)$$

$$L_{j,k} \geq d_j * \sum_{v < a} X_{v,j,k}; \forall k, \forall j \quad (14) \quad T2_{a,k1} \geq T3_{a,k1} - R - w_2 * (1 - Y_{k,k1}); \quad \forall k, \forall k1, k \neq k1 \quad (28)$$

$$L_{j,k} \leq Q * \sum_{v < a} X_{v,j,k}; \forall k, \forall j \quad (15) \quad T2_{a,k} \geq T3_{a,k1} - R - w_2 * (Y_{k,k1}); \forall k, \forall k1, k \neq k1 \quad (29)$$

$$L_{v,k} + (d(v1) * X_{v,v1,k}) \leq L_{v1,k} + C * (1 - X_{v,v1,k}); \quad \forall v, \forall v1 \leq a, \forall k \quad (16) \quad T4_{m,k} \geq w_1 * \sum_j X_{k,j,k}; \forall k, \forall m \quad (30)$$

$$L_{v,k} + (d(v1) * X_{v,v1,k}) \geq L_{v1,k} - C * (1 - X_{v,v1,k}); \quad \forall v, \forall v1 \leq a, \forall k \quad (17) \quad T4_{m,k} \leq w_2 * \sum_j X_{k,j,k}; \forall k, \forall m \quad (31)$$

$$L_{v1,k} \leq C * \sum_v X_{v,v1,k}; \forall v1 \leq a, \forall k \quad (18) \quad T1_{v,k} \leq w_2 * \sum_{v1} X_{k,v1,k}; \forall k, \forall v < a \quad (32)$$

$$L_{\theta_k,k1} = 0; \forall k, \forall k1 \quad (19) \quad T2_{a,k} \leq w_2 * \sum_j X_{k,j,k}; \forall k \quad (33)$$

The second group of constraints refers to the school bus transportation system. Expression (8) forces all students to be picked up only once. Expressions (9) and (10) are related to the flow conservation at nodes that represent students and the highway. They guarantee that if a bus picks up a student, it continues the route leaving the node visited. Eq. (11) guarantees that each route starts from its own starting point. Eq. (12) guarantees that when a bus picks up students, it leaves from its own base. Expression (13) guarantees that the node that represents the highway is included in all the routes used. Eq. (14)-(15) control the number of students that are being picked up at node visited (in this case, one student), and that the bus capacity is respected. Expressions (16) and (17) compute the total number of students a bus picks up. Eq. (18) guarantees that a bus adds children when that bus picks them up. Finally, eq. (19) guarantees that buses are empty when they start each route.

$$T1_{v,k} + s(v) + ti(v, v1) \leq T1_{v1,k} + w_2 * (1 - X_{v,v1,k}); \quad \forall v, \forall v1 < a, \forall k \quad (20) \quad X_{v,v1,k}, Y_{k,k1} = \{1, 0\}, \forall v, \forall v1, \forall k, \forall k1 \quad (35)$$

$$T1_{v,k} + (s(v) + ti(v, v1)) * X_{v,v1,k} \geq T1_{v1,k} - w_2 * (1 - X_{v,v1,k}); \quad \forall v, \forall v1 < a, \forall k \quad (21) \quad L_{v,k}, T1_{v,k}, T2_{a,k}, T3_{a,k}, T4_{m,k}, Z \geq 0; \forall v, \forall k, \forall m \quad (36)$$

$$\sum_k X_{v,v1,k} + \sum_k X_{v1,v,k} \leq 1; \forall (v < a), \forall (v1 < a) \quad (37)$$

The third group of constraints controls the time variables and guarantees the right sequencing of buses at the highway. Expressions (20) to (27) limit the time from the moment bus k starts a route, picks up students, and travels along highway a , until it finishes in school m . Expression (28) guarantees sequencing when bus k precedes bus $k1$, by respecting a minimum amount of time R , in which bus $k1$ cannot enter the highway. Eq. (29) guarantees the consistency between arrival time of bus k to the highway and the leaving time of bus $k1$ to the highway when bus k does not precede bus $k1$. Further, eq. (30)-(31) guarantees that children arrive on time to schools (within the time window). Expressions (32)-(34) guarantee that if a bus k does not start a route, its time $T1$, $T2$, and $T3$ are not calculated.

$$\sum_j X_{\theta_{k+1},j,k+1} \leq \sum_j X_{\theta_k,j,k}; \forall k \quad (38)$$

$$\sum_{v < a} \sum_{k > j} X_{v,j,k} = 0; \forall j \quad (39)$$

Finally, the fourth group of constraints (35)-(36) guarantees the nature of the binary and positive variables, respectively. The previous groups of constraints lead to the single load base model. Moreover, there is a last group of expressions known as valid inequalities, which increase the efficiency of the model. Details will be given in section 5. Expression (37) avoids the generation of sub-trips between two nodes visited consecutively. Eq. (38)-(39) guarantee that routes are generated in ascending order.

3.1. Mathematical formulation for school bus routing and scheduling problem – mixed load strategy

The formulation for the mixed load strategy is similar to that of the single load strategy. Additional sets, parameters, variables and expressions will be presented in this numeral. In each case, the elements that remain constant for both models will be explicitly shown. For this strategy, the sets j , k , θ_k , a , $v1$, $j1$, and $k1$ remain the same as in the single load strategy. Let set m be the destination schools. We include the node f representing a fictitious node where all routes finish. The parameters Q , dj , sj , $w1$, $w2$, C , $ti(v,v1)$, $Cv(v,v1)$, C and R remain the same in this model. Now, the parameter denoted as ϕ_{jm} is a binary parameter indicating if the student j goes to school m . The set $v: \{\theta_k\} \cup \{j\} \cup \{a\} \cup \{m\} \cup \{f\}$, where $\theta_k < j < a < m < f$. $m1$ is a copy of m .

In addition to decision variables $X_{v,v1,k}$, $Y_{k,k1}$, $L_{v,k}$, $T1_{v,k}$, $T2_{a,k}$, $T3_{a,k}$, $T4_{m,k}$ that remain the same in this model, the following decision variables are included: let $W_{v,k}$ be equal to 1 if node v is visited by bus k , otherwise let it be equal to 0. Also, let $T5_{m,k}$ be the arrival time of bus k at school m . The function objective of mixed load model is the same as expression (1) of the single load model. The following constraints are considered:

$$\sum_k X_{a,f,k} = 0; \forall k \quad (40)$$

$$X_{f,v,k} = 0; \forall v, \forall k \quad (41)$$

The first group of constraints contains the expressions (2)-(5) and (7) of the single load model. The added expressions (40) guarantees that going directly from the node a to the fictitious node is not allowed (used in the mixed load as final point of routes), and (41) guarantees that bus k does not visit more nodes after finishing the route on the fictitious node f .

In the second group, constraints remain the same as expressions (8)-(19) of the single load. Additionally, the following constraints, for the mixed load model, are defined:

$$\sum_v X_{v,m,k} \leq W_{m,k}; \forall m, \forall k \quad (42)$$

$$\sum_v \sum_k X_{v,m,k} \geq 1; \forall m \quad (43)$$

$$L_{v1,k} \leq C * W_{v1,k}; \forall v1 \leq a, \forall k \quad (44)$$

$$W_{v,k} \leq W_{v1,k}; \forall (k < v < a), \forall (v1 > a), \forall k, \forall (v, v1) | \phi_{(v,v1)} > 0 \quad (45)$$

$$\sum_{v1} X_{v,v1,k} \geq W_{v,k}; \forall v, \forall k \quad (46)$$

$$\sum_{v1} X_{v,v1,k} \leq W_{v,k}; \forall v, \forall k \quad (47)$$

$$\sum_m X_{m,f,k} \leq 1; \forall k \quad (48)$$

Expression (42) guarantees that bus k visits school m only once if it delivers students of that school, while eq. (43) guarantees that school m is visited at least once for bus k . Expression (44) guarantees that bus k only cumulates children when they are effectively picked up by this bus. Eq. (45) guarantees that when a student is picked up in route k , this is delivered to the school destination. Expressions (46) and (47) guarantee that if a student is picked up by a bus k , it only has one predecessor node. Finally, eq. (48) guarantees that bus k finishes the route at fictitious node f after delivering students to schools.

In the third group of constraints, expressions (20) to (29) and (32) to (34) stay as in single load model. Moreover, the following expressions, for the mixed load model, are defined:

$$T4_{m,k} + s(m) + ti(m, m1) \leq T5_{m1,k} + w_2 * (1 - X_{m,m1,k}); \forall m, \forall m1, \forall k \quad (49)$$

$$T4_{m,k} + (s(m) + ti(m, m1)) * X_{m,m1,k} \geq T5_{m1,k} - w_2 * (1 - X_{m,m1,k}); \forall m, \forall m1, \forall k \quad (50)$$

$$T5_{m,k} + s(m) + ti(m, m1) \leq T5_{m1,k} + w_2 * (1 - X_{m,m1,k}); \forall m, \forall m1, \forall k \quad (51)$$

$$T5_{m,k} + (s(m) + ti(m, m1)) * X_{m,m1,k} \geq T5_{m1,k} - w_2 * (1 - X_{m,m1,k}); \forall m, \forall m1, \forall k \quad (52)$$

$$T4_{m,k} \geq w_1 * X_{a,m,k}; \forall k, \forall m \quad (53)$$

$$T4_{m,k} \leq w_2 * X_{a,m,k}; \forall k, \forall m \quad (54)$$

$$T5_{m,k} \geq w_1 * W_{m,k}; \forall k, \forall m \quad (55)$$

$$T5_{m,k} \leq w_2 * W_{m,k}; \forall k, \forall m \quad (56)$$

$$X_{v,v1,k}, Y_{k,k1}, W_{v,k} = \{1, 0\}; \forall v, \forall v1, \forall k, \forall k1 \quad (57)$$

$$L_{v,k}, T1_{v,k}, T2_{a,k}, T3_{a,k}, T4_{m,k}, T5_{m,k}, Z \geq 0; \forall v, \forall k, \forall m \quad (58)$$

Eq. (49)-(52) calculate and control the time in which bus k arrives at node $m1$, immediately after visiting node m .

Expressions (53)-(56) guarantee that students are delivered to schools at the established time. Constraints (57)-(58) guarantee the nature of binary and positive variables. Expressions (37)-(39), mentioned in the single load model, are used in this model as well.

4. Proposed solution methodology

A heuristic method is proposed to find near-optimal solutions to the problem and to keep better control of the computational times. The algorithm starts with a constructive approach known as “cluster first-route second”. This procedure consists of clustering students to assign them to each bus. Then, the sequence of students is computed. This approach has been applied by [25], who solved a pick-up and delivery routing problem, and [26], who develop a tabu search meta-heuristic to solve a problem that included the load balance of vehicles. Fig. 2 shows the flowchart of the heuristic for the single load and the mixed load strategies.

The first step of the algorithm is to calculate the target number of buses. This corresponds to the integer obtained after rounding up the result of the relation j/Q . Then, the algorithm searches for homogeneous generation of clusters in relation to the number of children. To do so, clusters are built by dividing the y-axis of the geographical plane, in such a way that the number of students in each cluster is balanced. A nearest-neighbor routing heuristic is applied to determine the sequence in which students are picked up and the schools that are visited (for the case of the mixed load strategy). This approach is also used by [26]. The proposed approach is similar to the one presented by [27], their metaheuristic approach solves the generalized elementary shortest path problem, which consists on finding a shortest path from a known location to a known destination by visiting clusters of nodes where a profit is collected.

Finally, the “longest processing time” rule from machine-scheduling heuristic is used to determine the order and the time intervals in which routes will be performed. The objective of this is to sequence the buses at the node that represents the highway to avoid heavy congestion. The proposed algorithm uses a backward scheduling approach, starting with the longest route to the shortest one. This tries to guarantee that the longest route arrives within the time window limit at the schools. Thus, the second-longest route is scheduled to enter the highway with a delay of R time units after the previous route is scheduled. The procedure is repeated for the other routes until the shortest route is scheduled. In the case in which an infeasibility is generated because the length of the route is longer than the defined timeline (from 0 to w_2), the algorithm starts the process again, increasing in 1 the number of clusters and until the maximum number of clusters is equal to the number of students.

5. Numerical Example

A numerical example is presented to present some insights of the problem. For this example, three instances of the single load model are solved independently, each one with six students. Then these are combined to solve a mixed load system with 18 students and three schools (Instance 6-18). In Fig. 3, the obtained geographical distribution for the different set of nodes is shown.

Figure 4 shows the solutions obtained when these

instances were solved under the single load strategy. In this case, the optimal solution for the instances of School1, School2, and School3 were found in 0.19, 0.27, and 0.21 seconds respectively (0.67 seconds in total). After running the solution to solve this instance with the mixed load strategy, the optimal solution was obtained in 17 minutes. It is shown in Fig. 5.

Tables 1-3 show the arrival times for single load routes, illustrated in Fig. 4. Tables 4 and 5 present the corresponding times to mixed load routes, represented in Fig. 5.

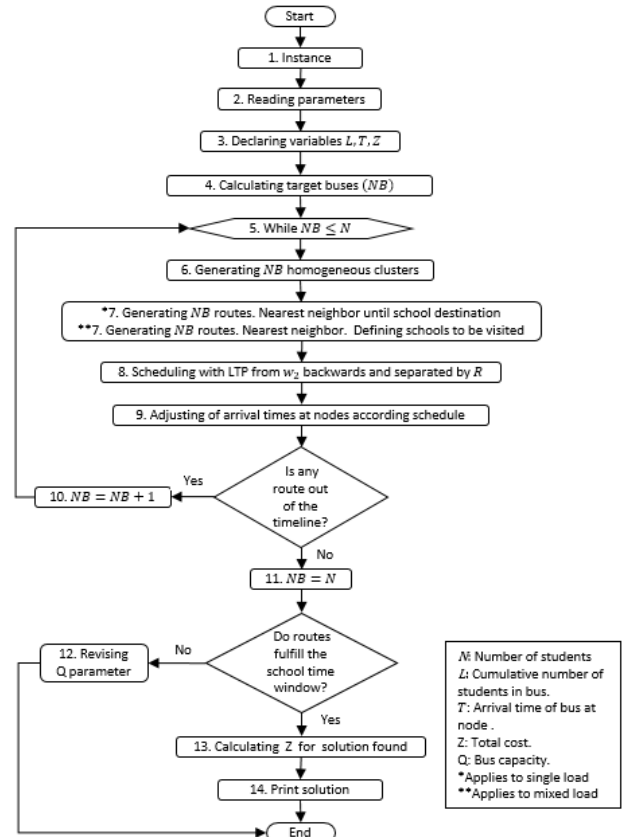


Figure 2. Flowchart of developed heuristic.

Source: prepared by authors

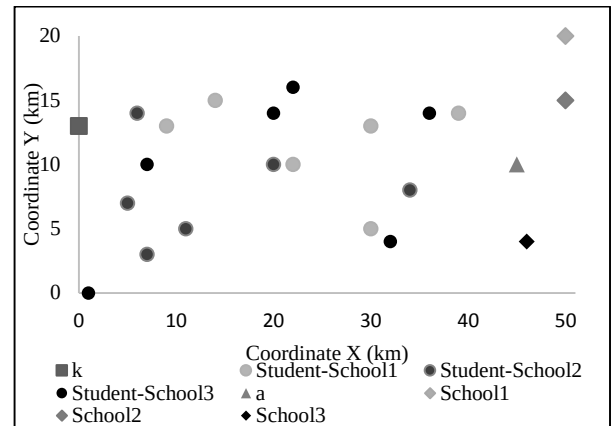


Figure 3. Geographical distribution of nodes for instance 6 with 18 students.

Source: prepared by authors

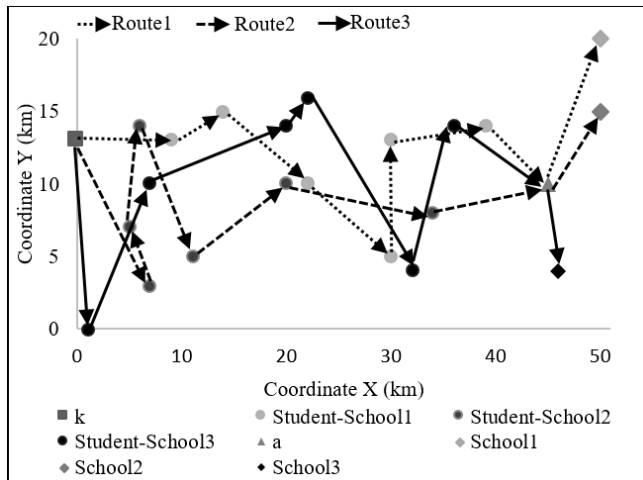


Figure 4. Single load solution for instance 6 with 18 students.
Source: own elaboration

Table 1
Single load strategy – Arrival times for route 1

Route	Node	Arrival Time	Arrival Hour
Route1	1	0	5:00
	10	18	5:18
	8	27	5:27
	12	43	5:43
	11	59	5:59
	7	73	6:13
	9	89	6:29
	13in	102	6:42
	13out	132	7:12
	14	150	7:30

Source: prepared by authors

Table 2.
Single load strategy – Arrival times for route 2

Route	Node	Arrival Time	Arrival Hour
Route2	1	0	5:00
	10	12	5:12
	12	20	5:20
	9	33	5:33
	7	51	5:51
	8	69	6:09
	11	93	6:33
	13in	112	6:52
	13out	142	7:22
	14	154	7:34

Source: prepared by authors

The mixed load strategy, on the contrary, guarantees collaborative planning. In this manner, the entry of buses to the highway is carried out in an orderly and coordinated way for all schools, as shown in Tables 4 and 5. For this case, the arrival time is at 07:05 and 07:20, respectively. In other words, buses arrive 15 minutes apart ($R=15$), minimizing the bunching effect. Fig.6 shows a Gantt graph of the arrival times at the highway for the different routes of the two strategies.

Table 3
Single load strategy – Arrival times for route 3

Route	Node	Arrival Time	Arrival Hour
Route3	1	0	5:00
	9	27	5:27
	12	48	5:48
	7	72	6:12
	8	78	6:18
	10	106	6:46
	11	125	7:05
	13in	143	7:23
	13out	173	7:53
	14	183	8:03

Source: prepared by authors

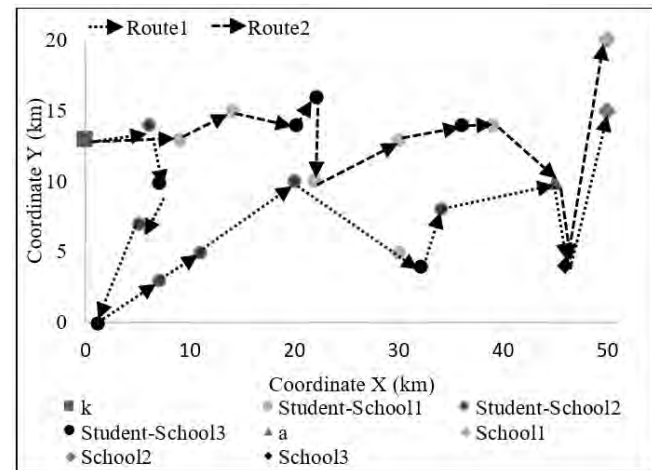


Figure 5. Mixed load solution for instance 6 with 18 students.
Source: prepared by authors

Table 4
Mixed load strategy – Arrival times for route 1

Route	Node	Arrival time	Arrival hour
Route1	1	13	5:13
	22	28	5:28
	20	37	5:37
	31	48	5:48
	32	54	5:54
	24	65	6:05
	23	81	6:21
	19	95	6:36
	35	106	6:46
	21	112	6:52
	37in	125	7:05
	37out	155	7:35
	40	165	7:45
	38	193	8:13

Source: prepared by authors

6. Computational results

Random instances are built to do experiments. To generate the data, the following assumptions are considered: the geographical location per node is random on a Cartesian plane of 50 kilometers on the horizontal axis (coordinate x), and 20 kilometers on the vertical axis (coordinate y). This plane has an area of 1000km², which represents approximately 75%

Table 5
Mixed load strategy – Arrival times for route 2

Route	Node	Arrival time	Arrival hour
Route2	2	11	5:11
	27	21	5:21
	36	29	5:29
	30	37	5:37
	33	51	5:51
	28	64	6:04
	25	72	6:12
	26	90	6:30
	34	113	6:53
	29	121	7:01
	37in	140	7:20
	37out	170	7:50
	40	180	8:00
	39	201	8:21

Source: prepared by authors

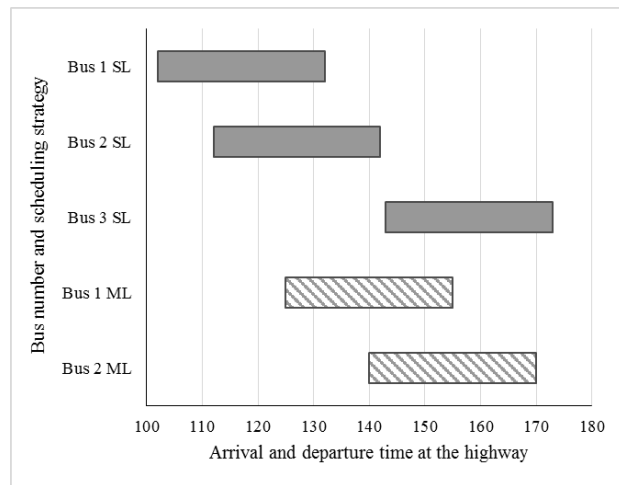


Figure 6. Gantt chart for the scheduling of buses on the highway.

Source: prepared by authors

of the area of Bogota. The timeline starts from 05:00a.m. to 08:30a.m. in minutes (0 to 210 minutes).

The time window for the school is from 07:30a.m. - 08:30a.m. The average time taken in traffic congestion to travel along the highway is 30 minutes, and the average speed is 36 km/hour. There are as many available buses as students, that is, $k=j$, and each bus has a capacity of 10 students. At each stop, the bus picks up only one student. The time one bus spends to pick up one student is 1 minute. That is, buses must be scheduled at least 15 minutes apart when they are about to enter to node that represents the highway ($R = 15$ minutes). The fixed cost is 50 currency units. The variable cost relates to the covered distance; it is assumed to be five (5) currency units/km.

Experiments are carried out using solver GAMS v. 23.5.1 on a personal computer with an Intel® Core™ i3-2310M 2.10GHz processor 8 Gb RAM. 51 instances are generated, which vary from four (4) to 20 students (three (3) different instances for the same problem size). The optimal solution is found in 21 instances, an integer solution is found in 23 instances, and no solution is found in seven (7) instances with a time limit of four (4) hours. All the above demonstrate the complexity of the problem to be solved, since optimal solutions are found only for instances with 10 students.

According to this, valid inequalities are proposed to make the mathematical model more efficient, and in this manner, optimal solutions for more instances are computed.

For the case of the model with valid inequalities (WVI Model), the optimal solutions for 27 instances are found, an integer solution are found in 16 cases, and no solution is found in eight (8) cases. Additionally, a comparative analysis is carried out in terms of time for the 21 instances, in which an optimal solution is found, either with the base model as with WVI Model. Thus, the average time for the base model is 309.1 seconds while the average time for the WVI model is 7.87 seconds. In conclusion, for the sample of 21 instances, the WVI Model needs 2.5% of the base model time to find the optimal solution.

Table 6 shows the consolidated results according to the size of the instances (N) for both cases. Column "CPU[s]" corresponds to the average solver run time in seconds. Column "Cost" refers to the average objective function value. Finally, column "O.S.F." presents the number of optimal solutions found per instance size group.

The WVI single load model structure is used to develop the mixed load model. Ten (10) instances are taken into account combining single load instances to obtain a system with multiple schools of mixed load, and in that way, carry out a comparative analysis between the two strategies, maintaining equality in the conditions of the two systems.

Table 7 shows the results for the mixed load strategy instances and the comparison with the added results obtained with single load strategy, based on the size of the instance (8-21). The column "N.R." refers to the number of buses needed in the solutions. The column "CPU[s]" corresponds to execution time in seconds. The column "Cost" refers to the objective function value. A bold font is used to highlight when an optimal solution is found. The relationship in terms of cost (R.C) of mixed load strategy over single load strategy is also presented. (OOM means "Out of memory").

For the generated mixed load instances, the optimal solution for seven (7) out of 10 instances is found, an integer solution is found for two (2) instances, and the computer ran out of memory once. It is important to highlight that, for these nine (9) instances, the average number of routes used and the objective function value with mixed load strategy correspond to 74%, and 77% of the single load strategy, respectively.

Additionally, in terms of computational time, the mixed load strategy is not competitive in terms of time when compared to the results of the single load. In this case, it is necessary to develop a heuristic method focused on improving this measure, since in instances with sizes adapted to reality, the tool should facilitate decision making in reasonable times.

The proposed heuristic algorithm is implemented in Python. In the following, a comparative analysis of the heuristic method and the commercial solver is presented.

Table 8 shows the consolidated results based on the size of the instances (N) for both methods and the single load strategy. The column "Cost" refers to the objective function value. The column "CPU[s]" corresponds to the average time of the run in seconds. The column "N.O.S" refers to the number of optimal solutions found in instances with a determined size. The column "GAP" refers to the absolute percentage deviation of the cost obtained with the heuristic method, according to the cost of the best known solution for each of the instances.

Table 6

Comparative results by solver of single load model with and without valid inequalities.

N	Base Model			WVI Model		
	CPU[s]	Cost	O.S.F.	CPU[s]	Cost	O.S.F.
4	0,2	373	3	0,1	373	3
5	0,4	398	3	0,2	398	3
6	0,7	428	3	0,2	428	3
7	2,3	427	3	0,3	427	3
8	3,0	480	3	0,4	480	3
9	1.936,4	525	3	52,8	525	3
10	220,8	487	3	1,1	487	3
11	8.169,7	747	-	7.129,4	747	2
12	13.284,9	713	-	8.481,4	712	2
13	3.915,3	742	-	10.586,2	735	2
14	6.280,4	742	-	4.837,1	742	-
15	3.770,4	728	-	7.001,4	725	-
16	13.980,5	787	-	5.097,2	785	-
17	3.860,6	788	-	1.800,6	840	-
18	2.250,7	1.200	-	2.600,7	788	-
19	N.S.F	N.S.F	-	3.600,8	800	-
20	4.001,1	840	-	10.201,0	840	-

Source: prepared by authors

Table 7.

Comparative results by solver between mixed load and single load strategies

Instance	Mixed load strategy			Single load strategy			R.C
	N.R.	CPU [s]	Cost	N.R.	CPU [s]	Cost	
1-8	1	0,5	510	2	0,2	755	68%
2-15	2	74,9	820	3	0,4	1.110	74%
3-10	1	1,6	480	2	0,3	845	57%
4-15	2	73,6	815	3	0,5	1.195	68%
5-12	2	27.805,9	710	2	0,5	795	89%
6-18	2	1.021,9	965	3	0,7	1.285	75%
7-14	OOM	OOM	OOM	2	0,6	905	-
8-21	3	20.001,2	1.200	3	0,8	1.280	94%
9-13	2	68,9	860	3	0,4	1.160	74%
10-16	3	9.300,6	1.215	3	0,5	1.280	95%

Source: prepared by authors

As observed in Table 8, with the commercial solver, 27 optimal solutions are found, while with the heuristic method 12 (56% less). Nevertheless, the average percentage (%) gap for the solutions with the heuristic method in relation to solver is 7.3%. This suggests competitiveness of the heuristic method. In the case of the solver, it is not possible to find a solution for eight (8) of the 51 instances, while the heuristic method attained a solution for each of the instances. To conclude, it is important to highlight the efficiency of computational time using the heuristic method; it required 0.12% of the average time used by the solver. In other words, there is a reduction of 99.88%.

To prove the capability of the heuristic method, three (3) random instances with 100 students are generated, in which the parameters are modified as follows: $R=15$, $Q=30$, $S_f=0$, $S_a=10$, and $V=50$. By running the algorithm, solutions with four (4) routes for each instance, with an average cost of 1,698.0 currency units in an average time of 0.001 seconds, are obtained.

Table 9 shows the obtained results for the instances developed with mixed load strategy, both with the heuristic

Table 8

Comparative results between the commercial solver and the heuristic for the single load strategy

N	Solver			Heuristic			
	Cost	CPU[s]	N.O.S	Cost	CPU[s]	N.O.S	GAP
4	373	0,1	3	373	0,0	3	0,0%
5	398	0,2	3	400	0,0	2	0,4%
6	428	0,2	3	438	0,0	1	2,3%
7	427	0,3	3	435	0,0	2	2,0%
8	480	0,4	3	583	0,0	1	21,5%
9	525	52,8	3	538	0,0	2	2,5%
10	487	1,1	3	652	0,0	1	33,9%
11	747	7.129,4	2	772	0,0	-	3,3%
12	712	8.481,4	2	768	0,0	-	8,0%
13	735	10.586,2	2	793	0,0	-	7,9%
14	742	4.837,1	-	798	0,0	-	7,6%
15	725	7.001,4	-	795	0,0	-	9,7%
16	785	5.097,2	-	800	0,0	-	1,9%
17	840	1.800,6	-	828	0,0	-	0,0%
18	788	2.600,7	-	873	0,0	-	10,9%
19	800	3.600,8	-	862	0,0	-	7,7%
20	840	10.201,0	-	870	0,0	-	3,6%
Avg.	637	3.611,2	27/51	681	0,0	12/51	7,3%

Source: prepared by authors

method as with the solver. The column "Cost" refers to the value of the objective function. The column "CPU[s]" corresponds to the run time in seconds. A bold font highlights if an optimal solution is found. The table also shows the column "GAP", which refers to the absolute percentage deviation of the obtained cost with the heuristic method according to the cost of the best known solution for each of the instances. (OOM stands for "Out of memory"). Seven (7) optimal solutions are found with the solver, while with the heuristic method only one. Nevertheless, the average GAP of the solutions with the heuristic method according to the solver is 7.8%. The case of the solver showed no solution for one (1) of the instances, while the heuristic method found one solution for each of the instances. The efficiency in terms of computational time of the heuristic method is important, since it spent in average only 0.02% of the time than the solver to find a solution.

Table 9.

Comparative results between the commercial solver and the heuristic for mixed load strategy

Instance	Solver		Heuristic		GAP
	Cost	CPU[s]	Cost	CPU[s]	
1-8	510	0,5	540	0,0	5,9%
2-15	820	74,9	975	0,0	18,9%
3-10	480	1,6	500	0,0	4,2%
4-15	815	73,6	825	0,0	1,2%
5-12	710	27.805,9	720	0,0	1,4%
6-18	965	1.021,9	1.345	0,0	39,4%
7-14	OOM	OOM	965	0,0	0,0%
8-21	1.200	20.001,2	1.285	0,0	7,1%
9-13	860	68,9	860	0,0	0,0%
10-16	1.215	9.300,6	1.025	0,0	0,0%
Avg	842	6.483,2	904	0,0	7,8%

Source: prepared by authors

An instance is generated by taking the three (3) largest instances generated with the single load strategy. It means, an instance with 60 students in which the parameters are modified as follows: $R=8$, $Q=15$, $S_v=0$, and $S_a=12$. This is

done to prove the efficiency of the heuristic method proposed. By running the algorithm, a solution with five (5) routes, with a total cost of 2,165.0 currency units in a time of 0.002 seconds is found.

7. Conclusions and future research

Different strategies are studied to optimize the use of buses in the school transportation system, in the case of Bogota. Mixed integer formulations are presented for the single load and mixed load strategies. The proposed modelling approach decides the sequence in which students are collected and the times at which the buses take the main road to the school zone in order to reduce traffic congestion. We propose a set of valid inequalities to improve the performance of the mathematical models. Further, a comparative analysis of the performance measures and benefits between both strategies is presented.

Results show that the mixed load strategy produces a better use of the resources. In the presented experiments, the number of buses is reduced in 25% in comparison to the single load strategy. Thus, fewer buses are needed in rush hours, less vehicle congestion is produced, and student travel times are reduced. Moreover, given the complexity of the problem, a heuristic method is developed to have better control of the CPU times. Competitive solutions are computed by the proposed method, with averages gaps between 7.3% - 7.8% in the optimal solutions. Future research includes considering special-education students; stochastic travel times; a heterogeneous fleet of buses; a multi-objective version of the models to minimize environmental impacts; other performance measures; and more sophisticated exact and heuristic methodologies.

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Differences between e-commerce buyers and non-buyers in Colombia: The moderating effect of educational level and socioeconomic status on electronic purchase intention

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Abstract

This study explores the differences between buyers and non-buyers in the adoption of electronic purchase intention in Colombia. Based on the Unified Theory of Acceptance and Use of Technology (UTAUT), a theoretical model that includes a set of five variables is established: performance expectations, effort expectations, social influence, facilitating conditions, and risk. The empirical results obtained from a final sample of 1,836 surveys emphasize the importance of performance expectations for both groups. Social Influence is another determinant of electronic purchase as well. In addition, an exploratory study of the moderating effect of the educational level and socioeconomic status for each group was performed, finding strong evidence of the influence of these demographic variables, which suggests that, as a conclusion that makes a great contribution to this country, access to electronic shopping is strongly related to educational level and socioeconomic status.

Keywords: e-commerce; UTAUT; purchase; Colombia; moderators; socioeconomic status; educational level.

Diferencias entre compradores y no compradores en el comercio electrónico en Colombia: El efecto moderador del nivel educativo y del estado socio-económico en la intención de compra electrónica

Resumen

Este estudio explora las diferencias entre compradores y no compradores en la adopción de la intención de compra electrónica en Colombia. Basado en la Teoría Unificada de Aceptación y Uso de la Tecnología (UTAUT), se establece un modelo teórico que incluye cinco variables: Expectativas de Rendimiento, Expectativas de Esfuerzo, Influencia Social, Condiciones Facilitantes y Riesgo. Los resultados empíricos obtenidos de una muestra final de 1.836 encuestas, resaltan la alta importancia de las Expectativas de Rendimiento que puede dar este canal comercial para ambos grupos, así mismo la Influencia Social es otro factor determinante de la compra electrónica. Así mismo, se realizó un estudio exploratorio del efecto moderador del nivel de estudios y nivel socioeconómico para cada grupo, encontrándose fuertes indicios de influencia de estas variables demográficas, lo cual permite suponer como conclusión de gran aporte para este país, que el acceso a la compra electrónica esta relacionada fuertemente con el estatus social.

Palabras clave: comercio electrónico; UTAUT; compra; Colombia; moderadores; nivel socioeconómico; nivel educativo.

1. Introduction

The rapid growth of services associated with the Internet

has dramatically changed the role of technology in business because the web has redefined the parameters for conducting business in general [1]. Through the Internet, inefficient

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markets are now more efficient, allowing small businesses the opportunity to engage with large businesses in a more competitive environment. From these changes, e-commerce appears as the final stage in the evolution of the Internet as a direct commercial channel changing traditional commercial marketing schemes [2].

There are various definitions of e-commerce in literature, with researchers and organizations having explained it according to the scope of their investigations or functions [3]. The World Trade Organization (WTO) defines e-commerce as *"the production, advertising, sale, and distribution of products via telecommunication networks"*, and the Global Center of Electronic Market defines it as *"Any form of transaction or exchange of information for commercial purposes in which the parties interact using information and communications technology (ICT), rather than by exchange or direct physical contact"* [4]. That is, e-commerce involves performing transactions via the Internet or another computer network, whenever the ownership of or use of property and/or services is transferred [5].

The adoption of information and communication technologies (ICTs), and particularly of electronic commerce, benefits businesses by increasing sales and reducing transaction costs because it enhances the understanding of customer needs, products, and services available in the market, increases the speed and efficiency of processes and organizational operations, targets advertising to everyone, and provides the ability to create virtual communities that become potential markets [5-7].

Various studies have been conducted to measure the adoption of electronic commerce geographically or by countries; most of these have focused considerable attention on factors that either facilitate or inhibit it [6]. These include the study conducted by [8] comparing the adoption of e-commerce in South Korea and Malaysia; [9] for Taiwan; [10] for Turkey; [11] in Italy; [12], who compares the countries of Pakistan, Portugal, and Austria; [13] for the US; [14] in Saudi Arabia; [15] in Spain; and [16] in Oman.

There are studies in Latin America such as that in Chile [17], however; the studies in this region are scarce. More research on e-commerce can be found in Colombia, and those completed by [18], which identify the antecedents of the intended use of e-commerce in the country, stand out. Meanwhile, [19] analyses how trust affects the intention to make online purchases, [4] identifies which factors affect such trust in buyers and non-buyers at the local level, and [20] measure the perception of the service quality of internet shoppers.

Given this context, the difficulties in determining the optimal conditions for the adoption of e-commerce, and the scarcity of research [6], this study aims to provide an analysis of how the intention of e-procurement is generated for buyers and non-buyers in Colombia through the empirical application of the Unified Theory of Acceptance and Use of Technology (UTAUT). Furthermore, two moderating variables, "socioeconomic status" and "educational level", are included as direct influencers of the relationship between extrinsic variables and purchase intention. In conclusion, this article intends to contribute to the study of electronic shopping in general in the following ways:

- 1) By establishing what are the variables involved in electronic purchase intention for Colombian electronic buyers and non-buyers, detecting their differences in the perception of this commercial channel.
- 2) By performing an exploratory analysis of the possible moderating effect of the variables of "socioeconomic status" and "educational level" for buyers and non-buyers on online purchase intention in general for a country with these characteristics.

The results can help governments and businesses develop strategies that motivate non-buyers to use this commercial channel and correct any failures regarding the buyer on the Internet, which is the future of commercial distribution in the 21st century.

This study is organized as follows: the first part reviews the related literature and proposes the hypotheses. It is followed by a section that specifies the methodology of the empirical study and its results. Finally, a section discusses the results and proposes future research.

2. Literature review

2.1. Technology acceptance model

Since early 1970, numerous models have been proposed to understand and explain the factors that determine the acceptance of the use of information technologies. Some of them examine the relationship between the attitudes, perceptions, and beliefs of technology users and the level of use of the technology itself [21]. They include the following:

2.1.1. Theory of Reasoned Action Model - TRA

The Theory of Reasoned Action (TRA) has been used to model consumer behaviour to assess the attitudes and beliefs of consumers; that is, it accounts for almost all types of human behaviour based on the beliefs and intentions of individuals [22,21].

The TRA proposes that an individual's behaviour is determined by his or her intention to behave and that this intention is influenced by attitudes and subjective norms. Although most of the support for the theory comes from the literature on social psychology, the TRA has been used successfully to identify key elements of consumer decision making and in several marketing fields. Therefore, several researchers have refined the TRA to improve its predictive character; two of these versions are the Technology Acceptance Model (TAM) and the Theory of Planned Behaviour (TPB) [23].

2.1.2. Technology of Acceptance Model - TAM

The Technology of Acceptance Model (TAM) is an instrument that emerged to estimate and predict how users accept emerging information technologies (ITs) that had gained popularity in the early 1980s. It was used to assess the potential market for a variety of new applications in the multimedia field and for image processing as well as to target investment in development activities [24].

The TAM uses the TRA as its theoretical basis for specifying

the causal links between the perceived usefulness of consumers, perceived ease of use, the attitude towards use, and the actual use of technology in particular [22,25]. That is, the model suggests that these variables are good indicators of the attitude and intention of potential users when choosing to use (or not use) technology based on initial perceptions [21].

2.1.3. Theory of Planned Behaviour - TPB

The TPB is an extension of the TRA in which the perceived control variable is incorporated as an antecedent of the intention/effective behaviour to observe the degree of control that the individual has on its behaviour. The variables in TPB are attitudes, subjective norms, and perceived control [26].

The TPB is one of the approaches most commonly used to explain different purchasing decisions because it has established the conceptual basis of much of the research focused on the study of consumer behaviour [26].

2.1.4. Decomposed Theory of Planned Behaviour - DTPB

From the TPB, Taylor and Todd [27] have developed the decomposed TPB (DTPB). This model aims to explain the behaviour of users based on the relationship between beliefs, attitudes, intention, and behaviour. According to this model, attitudes, subjective norms, and perceived behavioural control are the elements that help understand the reasons or factors that explain individual actions, even if the intention is regarded as the best indicator of behaviour [28].

2.1.5. Model of Personal Computer Utilization - MPCU

The Model of Personal Computer Utilization (MPCU), developed by Thompson, Higgins, and Howell [29], seeks to predict behaviour in the use of the PC (personal computer) based on Triandi's [30,31] theory of interpersonal behaviour (TIB), which argues that behaviour is determined by attitudes (what people would like to do), social norms (what they think they should do), habits (what they have typically done), and the expected consequences of their behaviour.

Thompson *et al.* [29] redefine Triandi's model [30,31] and suggest that people's behaviour in relation to the use of technology can be predicted by a combination of intended use based on attitudes, norms, and past behaviours. The MPCU takes into account how an individual uses the PC, what motivates him or her to use it, the social norms that establish the use of technology in the workplace, the habits of the person in relation to the PC, the benefits expected from the management of the computer, and the enabling conditions that make it possible to access it [32].

2.1.6. Diffusion of Innovations Theory - DIT

The Diffusion of Innovations Theory (DIT) was developed by Rogers [33] and has been used to study a variety of innovations. It identifies five attributes of innovation that influence adoption and acceptance behaviour: relative advantage, complexity, compatibility, trialability, and observability [32].

Subsequent to the empirical research of Rogers, a model of the proportions of adoption of the members of a social system has been obtained; these are predictable, regardless of the type of technology disseminated: innovators, early adopters, early majority, late majority, and dawdlers [32].

2.1.7. Social Cognitive Theory - SCT

Social Cognitive Theory (SCT) assumes that individual behaviour is not only an imitation of observed behaviour but also perfected by the individual according to the experiences and results achieved. In this manner, an individual's cognitive skills influence the behaviour of the use of technology, and the individual's successful experiences with technology also influence cognitive perception [34].

The highlight of this theory in studies of technological appropriation is the introduction of the concept of self-efficacy, which refers to the perception that a person has about his or her ability to successfully perform a task [32]. For SCT, all behaviour is defined by the interaction between the following elements: personal factors that characterize an individual, his or her behaviour, and the environment [34].

2.1.8. The Unified Theory of Acceptance and Use of Technology Model (UTAUT)

Due to the diversity of the technology acceptance models with similar theoretical foundations, initiatives to develop unifying models have emerged [34], including the UTAUT proposed by Venkatesh, Morris, Davis, and Davis [35]. The UTAUT was formulated from a conceptual and empirical synthesis of the above-mentioned models, providing a coherent theoretical perspective in the study of the adoption of online shopping [36].

The main concepts that group all of the adoption theories in the UTAUT are the following: performance expectation, expectation of effort, social influence, and enabling conditions; all of these influence the intention and use of technology behaviour [37] (Table 1).

Table 1.
Theories unified in the UTAUT.

Theory / Model	Construct	Correspondence /Construct UTAUT
Theory of Reasoned Action (TRA)	Subjective norm	Social influence (SI)
Technology Acceptance Model (TAM)	Perceived performance	Performance expectations (PE)
	Ease of use	Effort expectations (EE)
Motivational Model (MM)	Subjective norm	Social influence (SI)
	Extrinsic motivation	Efforts expectations (EE)
	Intrinsic motivation	
Theory of Planned Behaviour (TPB)	Subjective norm	Social influence (SI)
	Perceived control	Facilitating conditions (FC)
Diffusion of Innovations Theory (DIT)	Relative advantage	Performance expectations (PE)
	Ease of use	Effort expectations (EE)
	Image	Social influence (SI)
	Visibility	Facilitating conditions (FC)

Source: Adapted from [69]

Since its original publication, the UTAUT has served as a guiding model and has been applied to the study of a variety of technologies in both organizational and non-organizational [37] contexts. According to [38], the UTAUT is a model that can be very useful in describing the adoption of e-commerce in its initial development because, in more mature developments, many concepts lose significance. In addition, there is a lack of studies that use this model in countries where e-commerce has these characteristics.

Therefore, the following model hypotheses are proposed (Fig. 1):

2.1.9. Performance expectations

Performance expectations are understood as the degree to which the use of the system generates some benefits. In the case of the intended use of the electronic business channel, they refer to the benefits generated in relation to conventional shopping channels. This relationship is widely validated in the literature in studies applied to electronic commerce in general [8,18,37,39-41].

H1a: Performance expectations affect the intended use of electronic commerce by electronic buyers.

H1b: Performance expectations affect the intended use of electronic commerce by non-electronic buyers.

2.1.10. Effort expectations

These resemble the perceived ease of use concept and are the degree to which a buyer considers online buying easier and not very complex. Effort expectations are another variable that has been validated for the adoption of e-commerce [8,37,39-41]:

H2a: Effort expectations affect the intended use of electronic commerce by electronic buyers.

H2b: Effort expectations affect the intended use of electronic commerce by non-electronic buyers.

2.1.11. Social influence

Part of the subjective norm concept correlates the influence of social factors regarding intention and electronic shopping, which has previously been validated by several studies [37,39-41]:

H3a: Social influence affects the intended use of electronic commerce by electronic buyers.

H3b: Social influence affects the intended use of electronic commerce by non-electronic buyers.

2.1.12. Facilitating conditions

These group together the perceived behaviour control of technology and compatibility, referring to the degree perceived by the electronic buyer with respect to the support and infrastructure of the electronic channel; facilitating conditions have been validated as another influential factor for electronic purchase and intention [8,40,42,43].

H4a: Facilitating conditions affect the intended use of electronic commerce by electronic buyers.

H4b: Facilitating conditions affect the intended use of electronic commerce by non-electronic buyers.

2.1.13. Perceived risk

Perceived risk is the possible negative consequences arising from the use of purchase. Negative and positive influence relationships regarding electronic purchase have been found [42,44-46].

H5a: Perceived risk affects the intended use of electronic commerce by electronic buyers.

H5b: Perceived risk affects the intended use of electronic commerce by non-electronic buyers.

2.2. Probing new moderating variables of purchase intention

The UTAUT model makes use of moderating variables such as gender, age, the mandatory use of computer equipment, and the previous experience of users [32]. However, the adoption of electronic commerce can also be affected by other factors such as socioeconomic status and educational level [47], especially in countries where the digital gap is high [48].

Socioeconomic status determines the purchasing power of buyers. It is important because it has been estimated that innovations traditionally break into society via subjects of high socioeconomic status [33], and although there are no studies that analyse the moderating effect of socioeconomic status on models of e-commerce adoption, it has been found that users of e-commerce tend to have higher income levels [47].

Educational level is another traditional marketing variable, just like socioeconomic status. Adoption studies [49-51] show greater levels of buyers with high levels of education [52-56]. In this same approach, other authors find that higher levels of education convey more information to shop online. Therefore, educational level may affect variables such as effort expectations and ease of use, and perceived risk versus electronic shopping may be reduced [47,57,58].

From the above, the following hypotheses are proposed,

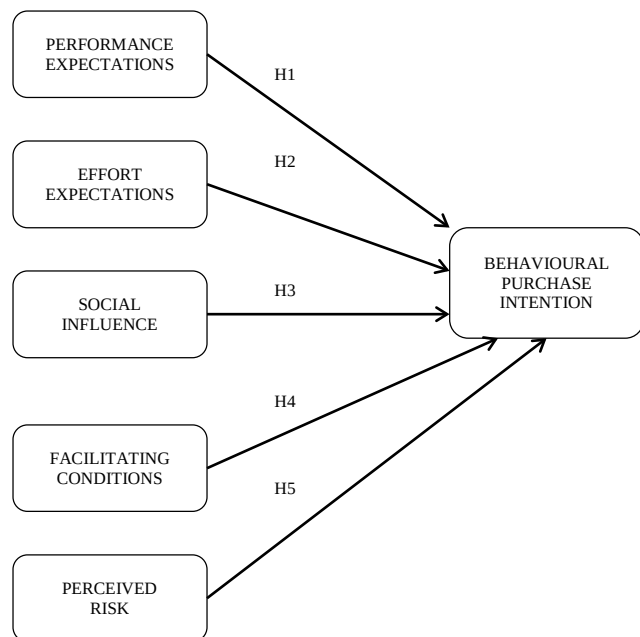


Figure 1. Proposed model from the UTAUT.
Source: The authors.

2.2.1. Moderating effects of socioeconomic status:

H6a: Socioeconomic status exerts a moderating effect on performance expectations and is related to the electronic purchase intention of online shoppers in Colombia.

H6b: Socioeconomic status exerts a moderating effect on performance expectations and is related to the electronic purchase intention of non-online shoppers in Colombia.

H6c: Socioeconomic status exerts a moderating effect on effort expectations and is related to the electronic purchase intention of online shoppers in Colombia.

H6d: Socioeconomic status exerts a moderating effect on effort expectations and is related to the electronic purchase intention of non-online shoppers in Colombia.

H6e: Socioeconomic status exerts a moderating effect on social influence and is related to the electronic purchase intention of online shoppers in Colombia.

H6f: Socioeconomic status exerts a moderating effect on social influence and is related to the electronic purchase intention of non-online shoppers in Colombia.

H6g: Socioeconomic status exerts a moderating effect on facilitating conditions and is related to the electronic purchase intention of online shoppers in Colombia.

H6h: Socioeconomic status exerts a moderating effect on facilitating conditions and is related to the electronic purchase intention of non-online shoppers in Colombia.

H6i: Socioeconomic status exerts a moderating effect on perceived risk and is related to the electronic purchase intention of online shoppers in Colombia.

H6j: Socioeconomic status exerts a moderating effect on perceived risk and is related to the electronic purchase intention of non-online shoppers in Colombia.

2.2.2. Moderating effects of educational level:

H7a: Educational level exerts a moderating effect on performance expectations and is related to the electronic purchase intention of online shoppers in Colombia.

H7b: Educational level exerts a moderating effect on performance expectations and is related to the electronic purchase intention of non-online shoppers in Colombia.

H7c: Educational level exerts a moderating effect on effort expectations and is related to the electronic purchase intention of online shoppers in Colombia.

H7d: Educational level exerts a moderating effect on effort expectations and is related to the electronic purchase intention of non-online shoppers in Colombia.

H7E: Educational level exerts a moderating effect on social influence and is related to the electronic purchase intention of online shoppers in Colombia.

H7F: Educational level exerts a moderating effect on social influence and is related to the electronic purchase intention of non-online shoppers in Colombia.

H7g: Educational level exerts a moderating effect on facilitating conditions and is related to the electronic purchase intention of online shoppers in Colombia.

H7h: Educational level exerts a moderating effect on facilitating conditions and is related to the electronic purchase intention of non-online shoppers in Colombia.

H7i: Educational level exerts a moderating effect on

perceived risk and is related to the electronic purchase intention of online shoppers in Colombia.

H7j: Educational level exerts a moderating effect on perceived risk and is related to the electronic purchase intention of non-online shoppers in Colombia.

3. Methodology

3.1. Measuring tool

Because the goal is to compare two groups of Internet users differentiated in terms of being non-users and users of electronic commerce, as explained when we built the model, a unique analysis of the basic variables that affect the electronic purchase is presented to use the same evaluating tool for the two groups. To test the hypotheses of the proposed model, items acquired from previous literature were used, choosing the measurement scale adapted from the Spanish study for the general adoption of electronic commerce in Spain [42]. Similarly, to avoid comprehension problems with regard to the questions when using the language, a pre-test was performed using a group of 50 Internet users representing various cities in Colombia to evaluate each of the questions, without major changes in the proposed final tool (Appendix 1).

3.2. Sample and data collection

Because this is an exploratory study for the entire Colombian territory and given that the population in this country is mostly concentrated in large urban areas, it was decided to select Internet users in the major cities of the country, such as Bogota, Medellin, Cali, and Barranquilla, as the target population. Correspondingly, each city generated an area that geographically and culturally integrated other nearby cities. From this point, it was determined to create a quota sampling, taking into account the selection of proportional data from each area as a first condition. The subsequent guidelines were for gender to be equitable and to disseminate the survey to all socioeconomic statuses of the population to avoid any possible bias. (Tables 2, 3)

The mechanism of data collection was performed through an electronic questionnaire validated in other studies for this type of research [40,42]. To facilitate the responses, the methodology that was followed entailed the use of a questionnaire with multiple items per construct; to provide their answers, the respondents used a Likert scale ranging from 1 (= "I strongly disagree") to 7 (= "I strongly agree") to effectively measure variables that are not directly visible [59].

The period for data collection occurred from November 2015 to May 2016. To achieve the objectives of the fieldwork, a national team with coordinators in each of the central cities was created to manage the distribution of the questionnaire. In addition, among the people who voluntarily responded to the survey, an incentive was offered, raffling a laptop that was given to the winner of the drawing held among all of the participants in June 2015 in Bogota and audited by the Gran Colombian Polytechnic University Institution (Institución Universitaria Politécnico Gran Colombiano). A total of 1,836 forms were obtained, of which 1,245 corresponded to online

Table 2.
Sample characteristics of Internet non-buyers.

Demographic profile		Adoption of Internet and e-commerce profile		
Gender: Male 46% Female 54%	Age:	Frequency of Internet use:		
	18-34 years old	Once per month		
	35-44 years old	1% Sometimes per month		
	45-55 years old	1% Once per week		
Educational level: Elementary 1% High school 29% Technical 32% University 35% Postgraduate 2%	Economic level (income ¹):	Sometime per week		
	Very low 17%	Daily use		
	Low 32%	Experience with Internet use:		
	Medium 32%	More than 10 years		
	Medium-high 13%	Between 5-10 years		
	High 5%	Between 1-5 years		
Civil Status: Single, Separated, Widower: 17% Married, Civil union: 83%	People cohabitating in the household:	Less than 1 year		
	1 person 6%	1%		
	2 persons 15%	Location:		
	3 persons 29%	Zone 1 (Antioquia, Caldas, Quindío Risaralda) 17%		
	4 persons 27%	Zone 2 (Bogota, Boyacá, Cundinamarca) 26%		

Zone 3 (Cauca, Valle del Cauca) 48%
Zone 4 (Atlántico, Bolívar, Cesar, San Andres, Magdalena, Santander) 8%
Zone 5 (Arauca, Caquetá, Huila Meta, Nariño, Tolima, Vaupes) 2%
¹ Adapted from the stratification used in Colombia according to public sources
Source: The authors.

Table 3
Sample characteristics of Internet buyers

Demographic profile		Adoption of Internet and e-commerce profile		
Gender: Male 49% Female 51%	Age:	Frequency of Internet use:		
	18-34 years 75%	Once per week 3%		
	35-44 years 17%	Daily use 97%		
	45-55 years 8%	Experience with Internet use:		
Educational level: Elementary 0% High school 17% Technical 26% University 41% Postgraduate 15%	Economic level (income ²):	More than 10 years		
	Very low 5%	50%		
	Low 21%	Between 5-10 years		
	Medium 44%	40%		
	Medium-high 19%	Between 1-5 years		
	High 10%	10%		
Civil Status: Single, Separated, Widower: 17% Married, Civil union: 83%	People cohabitating in the household:	Less than 1 year		
	1 person 9%	0%		
	2 persons 18%	Experience with e-commerce use:		
	3 persons 28%	More than 2 years		
	4 persons 55%	40%		

5 persons 16%	Between 6 months and 1 year 33%
Location:	
Zone 1 (Antioquia, Caldas, Quindío Risaralda) 25%	
Zone 2 (Bogota, Boyacá, Cundinamarca) 38%	
Zone 3 (Cauca, Valle del Cauca) 31%	
Zone 4 (Atlántico, Bolívar, Cesar, San Andres, Magdalena, Santander) 6%	
Zone 5 (Arauca, Caquetá, Huila Meta, Nariño, Tolima, Vaupes) 1%	

¹ Adapted from the stratification used in Colombia according to public sources
Source: The authors.

shoppers; 309 had consistency problems in the responses, and therefore, a final sample of 936 valid questionnaires for this group was obtained. Regarding the non-buyers, 875 forms were collected, and by eliminating 284 containing erroneous or inconsistent data, a final sample of 591 surveys for this group was obtained.

4. Data analysis and results

Latent variable regression analysis used in this study was conducted with the SmartPLS 2.0 program, which is based on the optimization technique of partial least squares (PLS). This is a multivariate technique for testing structural models that are exploratory in nature, and it has also been used to test the UTAUT model due to the large number of latent variables that it contains [40,60,61]. The analysis of the data was performed in two phases; the first assessed the measurement model, and the second examined whether the structural model was valid for both groups.

4.1. Validation of the measurement model

The validation process of the measuring instrument was performed from the exploratory analysis. The first step was to establish the convergent and discriminant validity of the constructs and the reliability of each item. The convergent

Table 4.
Indicator's loads for both groups.

Non-buyers			Buyers		
Indicator	Load	t-value*	Indicator	Load	t-value*
BI12	0.851	57.528	BI12	0.848	76.714
BI22	0.879	95.585	BI22	0.881	111.111
BI32	0.852	63.067	BI32	0.863	87.471
PE12	0.888	87.923	PE12	0.921	177.598
PE22	0.870	67.914	PE22	0.913	143.587
PE32	0.843	45.680	PE32	0.846	68.631
EE12	0.895	91.458	EE12	0.890	92.928
EE22	0.882	69.323	EE22	0.922	153.962
EE32	0.816	36.610	EE32	0.851	70.504
FC12	0.793	30.560	FC12	0.917	156.641
FC22	0.810	35.851	FC22	0.891	107.040
FC32	0.839	43.040	FC32	0.856	71.951
PR12	0.888	37.557	PR12	0.888	17.642
PR22	0.889	42.376	PR22	0.892	17.554
PR32	0.902	37.303	PR32	0.924	20.855
SI12	0.888	90.234	SI12	0.884	88.513
SI22	0.904	81.974	SI22	0.908	135.664

* All items had significance with p-value <0,001.
Source: The authors.

validity of each construct was acceptable because they all had loads higher than 0.505 [62]. The individual reliability of each item was measured by the correlation between their loads and each variable. Table 4 verifies that the loads for each indicator were significant and validated.

To calculate the internal measurement consistency of all indicators in relation to their corresponding variables, Dillon-Goldstein's test, known as the compound reliability coefficient, was applied; all values were higher than the acceptable minimum of 0.70 [63]. In addition, the Cronbach's alpha test was applied, obtaining for both groups values above 0.7, the minimum value allowed for confirmatory studies [59].

Finally, the convergent validity was analysed by once again taking into account the variance. In other words, there had to be a similar variance between the indicators and their construct, which must be greater than 0.50 of the variability explained by the indicators [64], being greater in the two groups (Table 5). The discriminant validity was verified by comparing the value of the average variance extracted (AVE) of each variable with the squared correlation of each construct's variable. The values obtained from the square root of the AVE were higher than those in the constructs, and therefore, it can be considered that each variable is more strongly related to their own items than to those of other variables, which is acceptable for both groups [64] (Tables 6 and 7).

4.2. Validation of the structural model

To continue with the structural model, another sampling was made through the bootstrapping technique. Using 1,000 sub-samples from the data of the study, a significant contrast of the model parameters was performed, all of the above, on the basis that the model has fulfilled its predictive ability by obtaining R^2 values greater than 0.10 [62]. The hypotheses

Table 5.
Convergent validity of the indicators.

Non-buyers			
Variables	Cronbach's Alpha	Compound reliability	Average variance extracted (AVE)
Facilitating conditions	0.750	0.855	0.663
Effort expectations	0.832	0.899	0.748
Performance expectations	0.835	0.901	0.752
Social influence	0.842	0.905	0.760
Purchase intention	0.825	0.895	0.740
Perceived risk	0.876	0.922	0.798

Buyers			
Variables	Cronbach's Alpha	Compound reliability	Average variance extracted (AVE)
Facilitating conditions	0.866	0.918	0.789
Effort expectations	0.875	0.923	0.799
Performance expectations	0.866	0.918	0.789
Social influence	0.845	0.906	0.763
Purchase intention	0.831	0.898	0.747
Perceived risk	0.887	0.929	0.813

Source: The authors.

Table 6.
Discriminant validity of the indicators – Fornell & Larcker Test.

Non-buyers						
	Facilit. Condit.	Effort Exp.	Perform. Exp.	Social influence	Purchase intention	Risk
Facilit. Condit.	0.814					
Effort Exp.	0.603	0.865				
Perform. Exp.	0.539	0.747	0.867			
Social influence	0.472	0.623	0.577	0.872		
Purchase intention	0.441	0.619	0.748	0.549	0.860	
Risk	0.303	0.331	0.262	0.175	0.202	0.89

Buyers						
	Facilit. Condit.	Effort Exp.	Perform. Exp.	Social influence	Purchase intention	Risk
Facilit. Condit.	0.888					
Effort Exp.	0.656	0.894				
Perform. Exp.	0.648	0.769	0.888			
Social influence	0.410	0.490	0.507	0.874		
Purchase intention	0.646	0.638	0.728	0.464	0.864	
Risk	0.144	0.059	0.046	0.062	0.098	0.90

Source: The authors.

Table 7.
Discriminant validity of the indicators – Henseler-Ringle test

	Facilit. Condit.	Effort Exp.	Perform. Exp.	Social influence	Purchase intention
Effort Expect.	0.761				
Perform. Exp.	0.673	0.798			
Social influence	0.586	0.743	0.686		
Purchase intention	0.549	0.744	0.797	0.657	
Risk	0.133	0.026	0.043	0.014	0.091

	Facilit. Condit.	Effort Exp.	Perform. Exp.	Social influence	Purchase intention
Effort Exp.	0.752				
Perfor. Exp.	0.747	0.776			
Social influence	0.478	0.569	0.592		
Purchase intention	0.759	0.740	0.753	0.550	
Risk	0.157	0.072	0.050	0.072	0.108

Source: The authors.

have been verified as follows: for the group of e-commerce users, the performance expectations variable was validated as having the highest incidence (H1a: $B = 0.457$), followed by effort expectations (H2a: $B = 0.071$), social influence (H3a: $B = 0.088$), and facilitating conditions (H4a: $B = 0.261$); although it was positive, the perceived risk construct was the only construct that was not significant (H5a: $B = 0.031$). For the non-online shoppers group, it was found that the variable with the highest incidence on future electronic purchase

intention is performance expectations (H1b: $B = 0.597$), followed by social influence (H3b: $B = 0.160$), and, finally, with low but valid incidence, effort expectations (H2b: $B = 0.078$). Conversely, for the non-users of e-commerce, the variables of facilitating conditions (H4b: $B = -0.001$) and perceived risk (H5b: $B = -0.008$) were not validated (Table 8) (Figs. 2 and 3).

Table 8.
Summary of the structural validity of the model.

Non-buyers					
Hypothesis	Original Sample (O)*	R squared	Standard Deviation (STDEV)	T Statistics (O /STDEV)	P Values
H4b Rejected	-0.001		0.038	0.014	0.989
H2b valid	0.078**		0.053	1.475	0.140
H1b valid	0.597*	Purchase Intention $R^2 = 0.588$	0.043	13.769	0.000
H3b valid	0.160*		0.041	3.915	0.000
H5b Rejected	-0.008		0.028	0.290	0.772
Buyers					
Hypothesis	Original Sample (O)*	R squared	Standard Deviation (STDEV)	T Statistics (O /STDEV)	P Values
H4a valid	0.261*		0.033	7.803	0.000
H2a valid	0.071*		0.040	1.750	0.080
H1a valid	0.457*	Purchase Intention $R^2 = 0.591$	0.040	11.492	0.000
H3a valid	0.088*		0.026	3.336	0.001
H5a Rejected	0.031		0.022	1.386	0.166

* $p < 0.001$, ** $p < 0.005$

Source: The authors.

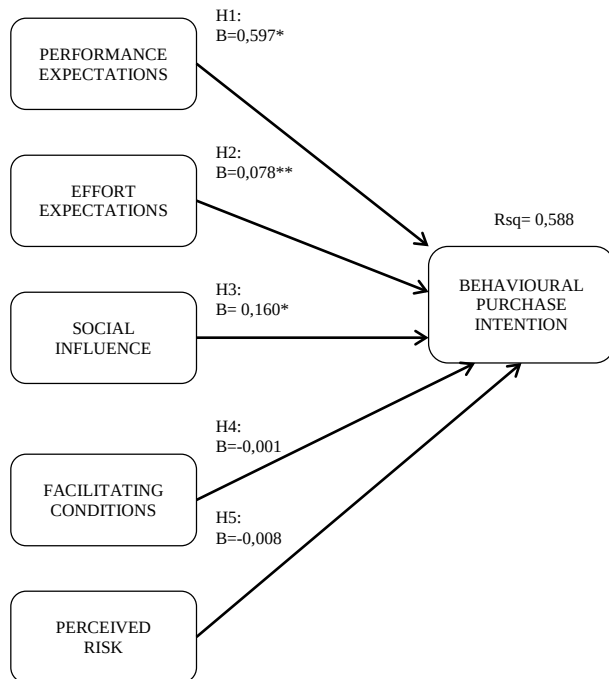


Figure 2. Model for e-commerce non-users
Source: The authors.

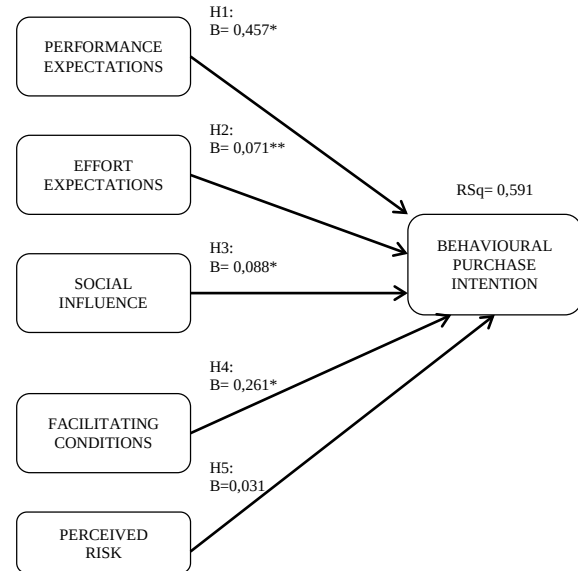


Figure 3. UTAUT model for e-commerce users
Source: The authors.

4.3 Analysis of the moderating effect of socioeconomic status

The moderating effect test for each of the model relations was applied, taking the socioeconomic status variable as the moderator. The results were that hypotheses H6g ($B = 0.040$) and H6h ($B = 0.056$) are significant for buyers, given that socioeconomic status exerts a positive moderating effect on the relationship between the facilitating conditions and purchase intention for both buyers and non-buyers. The remaining hypotheses are rejected (Table 9).

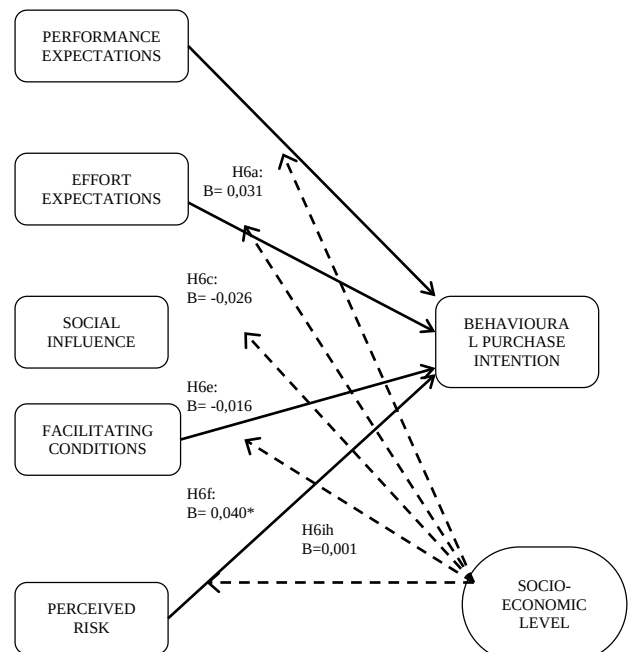


Figure 4. Moderating effects of socioeconomic status on purchase intention for electronic buyers.
Source: The authors.

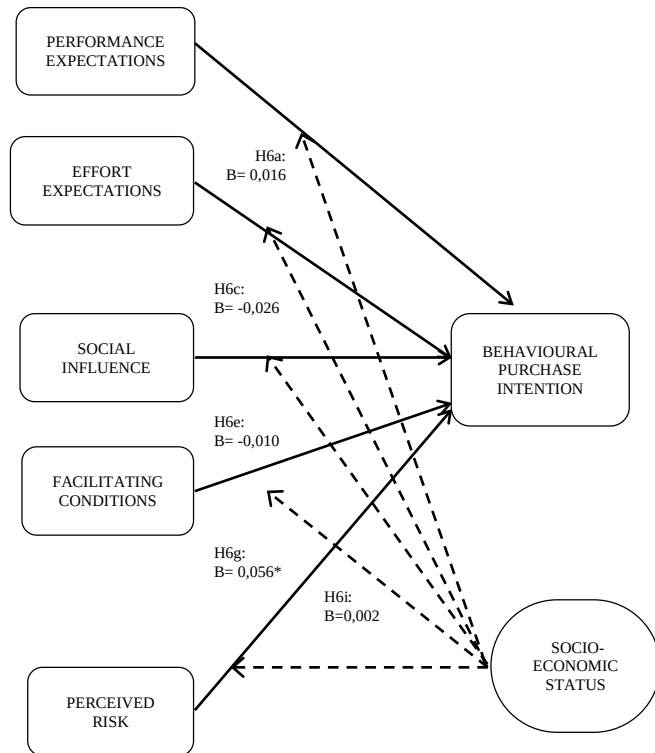


Figure 5. Moderating effects of socioeconomic status on purchase intention for electronic non-buyers.
Source: The authors.

4.4 Moderating effect of educational level

In the case of the moderating effects of educational level on non-online shoppers, hypothesis H7d ($B = 0.097$) is validated; that is, educational level has an effect that increases the positive influence of effort expectations on electronic purchase intention. The same occurs with hypothesis H7f ($B = 0.071$) because a higher educational level generates a greater social influence, affecting electronic purchase intention.

In the case of buyers, the following hypotheses were validated: H7g ($B = 0.065$), i.e., the higher the educational level is, the greater the incidence of facilitating conditions in electronic purchase intention; H7E ($B = 0.032$), i.e., educational level's positive effect on the relationship between social influence and electronic purchase intention is validated; H7c ($B = 0.022$), i.e., educational level exerts a positive effect on the relationship between effort expectations and electronic purchase intention; Finally, H7a ($B = -0.057$), i.e., educational level exerts a negative effect on the significance of the relationship between performance expectations and electronic purchase intention (Table 9).

Table 9.
Validation of moderating effects.

Electronic non-buyers				
Effect	Original Sample (O)*	Standard Deviation (STDEV)	T Statistics (O/STDEV)	P Values
economic->IS->IP	-0.010	0.045	0.056	0.564
economic ->ER->PI	0.016	0.051	0.326	0.745
economic ->PR->PI	0.002	0.029	0.061	0.952
economic ->-FC->PI	0.056*	0.043	1.898	0.095
economic ->EE->PI	-0.026	0.055	0.477	0.633
education ->PI	0.067	0.029	2.259	0.024
education->ER->PI	-0.111	0.042	0.618	0.239
education ->PR->PI	-0.007	0.029	0.229	0.819
education ->-EE->PI	0.097*	0.048	1.996	0.046
education ->-FC->PI	-0.010	0.039	0.265	0.791
education ->IS->PI	0.071*	0.046	1.850	0.043
education ->PI	0.019	0.028	0.684	0.494
Electronic buyers				
Effect	Original Sample (O)*	Standard Deviation (STDEV)	T Statistics (O/STDEV)	P Values
economic->CF-PI	0.040	0.019	0.032	1.890
economic ->IS-PI	-0.016	-0.017	0.026	0.626
economic ->ER-PI	0.031	0.031	0.039	0.798
economic -EE-PI	-0.026	-0.025	0.035	0.745
economic -R-PI	0.001	0.001	0.022	0.034
economic_ ->PI	0.060	0.001	0.198	0.020
education->CF-PI	0.065*	0.065	0.199	0.017
education ->EE-PI	0.022*	0.024	0.234	0.009
education ->ER-PI	-0.057*	-0.059	0.198	0.046
education ->IS-PI	0.032*	0.032	0.225	0.004
education ->PR-PI	-0.022	-0.020	0.032	0.864
education ->PI	0.043	0.013	0.221	0.021

Source: The authors.

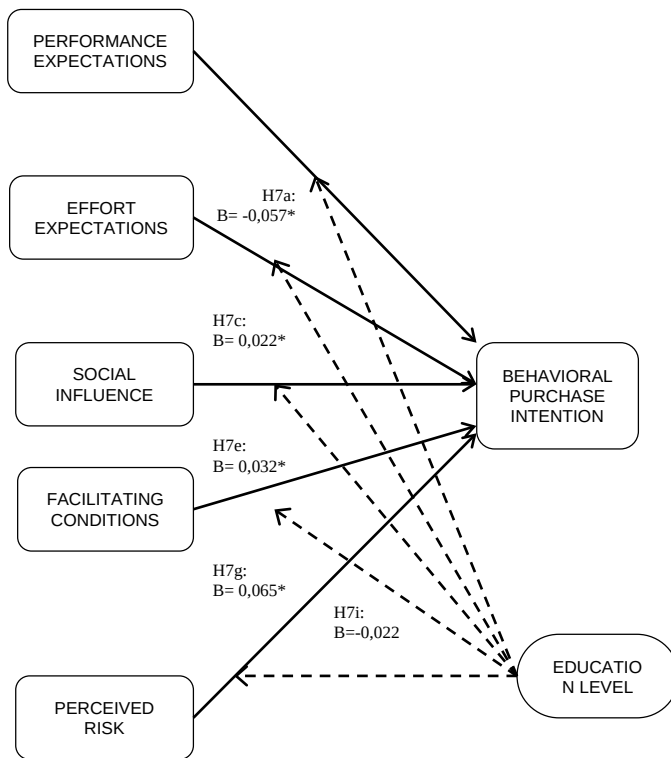


Figure 6. Moderating effects of educational level on purchase intention for electronic buyers.
Source: The authors.

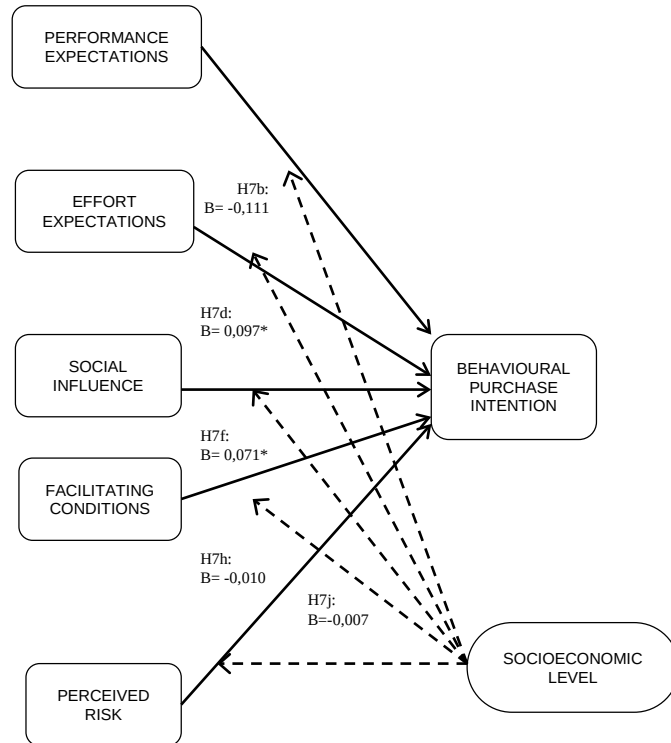


Figure 7. Moderating effects of educational level on purchase intention for electronic non-buyers.
Source: The authors.

5 Discussion

5.1 Theoretical contribution

This article aims to perform a comparative analysis between electronic buyers and non-buyers in Colombia with regard to the factors that affect electronic purchase intention. Similarly, through an exploratory analysis, it whether there is a moderating effect of the variables of socioeconomic status and educational level for both groups is examined. The results confirm that there are differences in the adoption of electronic purchase intentions between the two groups.

As a first theoretical contribution, the basic variables proposed in the UTAUT model concerning the adoption of electronic purchase intention [37,41] by electronic buyers have been validated, with a high incidence of performance expectations in both groups. This finding confirms one of the most important relationships in the literature for electronic consumers in other countries [9,40,65,66].

In addition, effort expectations are another factor that influences the intended use of e-commerce in Colombia for the group of buyers and that corresponds to previous studies that require the buyer to have motives that are related to the positive utility generated by the use of this technology [8,11,16,65,67,68]. Conversely, in the case of non-buyers, this variable has a very low validation because they may not perceive a high utility in using this commercial channel, which would be a major reason not to use it. This result can also relate to the DIT [33], in which late adopters dislike using something new because they feel that adopting it will not be necessary.

Following this validation order for the variables in the UTAUT model, another important predictor of the intention to use e-commerce is social influence, which has been positively validated for both groups, with a significant difference between them. First, regarding buyers, this relationship has a low validation, indicating that, possibly, relying on the statistics of the sample of experience in the use of e-commerce (approximately 70% of the online shopping for more than one year) (Table 3) may explain these results. According to [69], experience shows that buyers no longer take into account the opinions of others to make a utilitarian use of e-commerce. Additionally, for non-buyers, the experience is zero, which can therefore validate this relationship to a greater degree, given the same results in previous studies in which the adopters were beginners [14,39].

One variable linked to the tools facilitating the use of this technology is facilitating conditions, which have been validated for the group of buyers, confirming the proposal of the UTAUT model regarding electronic buyers' need to have technical conditions that enable them to make purchases effectively; however, this variable was not validated for non-buyers.

Finally, the perceived risk variable is not validated for the two groups. For buyers, although the perception of risk in online shopping is positive, it is not significant, which can be attributed to the perception of risk in business to consumer

(B2C) purchases, i.e., recognized websites and the security in banking system-related means of payment, leading to the rejection of this variable as a determinant of electronic purchase intention. In the case of non-buyers, this relationship is negative and very low; although this group is clearly distrustful of online shopping, the levels do not allow for verification.

To close this first analysis, the UTAUT model for the purchase intention of two groups of Internet users in Colombia (buyers and non-buyers) is verified. For buyers, the results consistently validate the relationships between the predictor variables and the dependent variable, noting that the R^2 is greater than 0.590 (Table 8), which reinforces that the model has measured a large proportion of the variables that a person takes into account to generate Internet purchase intention in general and according to previous studies of e-procurement in other countries [8, 40, 41, 66, 70]. For non-buyers, this study is one of the first to describe their intention to adopt e-commerce, equally validating the model as a good predictor of these relationships, with an R^2 of 0.588 (Table 8).

Regarding the exploration of the possible moderating effects of the socioeconomic status and educational level variables, this study has validated that socioeconomic status has a positive moderating effect on the relationship between the facilitating conditions and purchase intention variables for both groups (Figs. 4, 5). The above can be related to the studies of [33], who find that a higher economic level facilitates the access to and enjoyment of new technology, given that people with lower incomes are more affected by the cost of the goods that are necessary to connect to the Internet and, therefore, facilitating conditions are not considered to be an influential and positive factor [69]. Hence, this finding may be related to the fact that, in the non-buyers, the facilitating conditions variable is not significant because 49% of buyers have lower income levels (Table 3).

In addition, it has been found that educational level has a moderating effect on both groups (Figs. 6, 7), although this effect has been stronger for buyers in the following relationships: between social influence and purchase intention, effort expectations and purchase intention, and facilitating conditions and purchase intention; there is a negative moderating effect on the relationship between performance expectations and purchase intention. The results regarding educational level and its moderating effect regarding social influence may be because, when adopters gain more knowledge, they tend to share information related to their experiences among each other [33]. Social influence has been validated as influential in purchase intention, and buyers have a high degree of educational levels, with 81% of them having completed the first, second, and third cycles of higher education (Table 3), which supports the exploratory results for this group. The next moderating effect of educational level on the relationship between effort expectations and purchase intention has been proposed by [33], given that the higher the knowledge acquired is, the easier it is to handle technology. This may also explain the positive moderation in facilitating conditions, given that, for

people with higher education levels, it is easier to use e-commerce [15,42].

Finally, the negative moderating effect of educational level has been validated for this group with regard to the relationship between performance expectations and purchase intention. This may occur because a higher acquired knowledge tends to generate a more advanced use of e-commerce and, therefore, high experience, which may decrease the expectations regarding the benefits of its use for this group of buyers and become negative.

Finally, in the case of non-buyers, it has been shown that there is a positive moderating effect of educational level on the relationship between effort expectations and purchase intention, which may be logical for this group of e-commerce non-adopters. Given that, in the scale proposed by Rogers, people with higher levels of educational attainment are placed as innovative adopters because they are more knowledgeable, they tend to evaluate new technologies positively and as having high value [33,69]. Furthermore, the moderating effect exerted by the education of non-buyers on the relationship between social influence and electronic purchase intention is valid. These results can be equally related to the buyers, given that people who have more information and knowledge tend to share it among the other members of the community [33].

5.2 Practical and business contribution

This study contributes to describing the adoption of electronic purchase intention in a developing country, where studies related to this context are scarce [69]. The electronic consumer in Colombia considers e-commerce to be very valuable, which is reflected in their performance expectations, the strongest predictor of the intention to engage in electronic shopping. E-commerce is perceived as something useful that offers great benefits when used, which is a great opportunity for companies to market their products and services through this channel. In addition, effort expectations validate the characteristics of the electronic consumer with some experience to make this process easy.

Linked to this variable, the positive significance of facilitating conditions describes an overview of the access to the requirements for the use of this commercial channel, in which it can be assumed that the Colombian electronic consumer has all the necessary conditions to connect to the Internet, has valid means for making payments, and possesses the knowledge to perform the process. According to [33,48], all of this is directly affected by socioeconomic status, which is a factor that requires special attention given the current level of development of e-commerce in this country because consumers have high purchasing power and a profile that allow them to pioneer the use of new technologies.

This information is valuable for companies that market their products online in Colombia because they must take into account that the electronic consumer of this country has some interesting features for products and services focused on the medium-high segments. Simultaneously, however, this is not

a good sign, given that few people in this country use this commercial channel, with only 7% of the total population accessing Internet shopping [71]. For the non-buyers group, a large part of the population has a high perception of risk regarding the use of the Internet to make purchases, low positive utility in using this channel, difficulty of use, and lack of conditions needed to make purchases online, which are factors that are associated with the high digital gap [71] and which require a government policy to allow for more equitable and effective access and use of e-commerce in Colombia. Businesses are required to take into account that there is a high degree of mistrust in the use of this channel by those who still do not dare to use it, and they should disseminate strategies and policies for the promotion of electronic shopping.

5.3 Limitations

The main limitation of this study was that, even when a sample collection method by quota of all major Colombian cities was completed, a data spread across all age groups was not obtained. Although new communication and Internet technologies are used mostly by young people, a sample percentage of adults and older age people that would allow an analysis of this group within electronic buyers and non-buyers was not obtained.

Another aspect considered to be a possible limitation is that, when conducting a nationwide study that is exploratory in nature in terms of understanding the dynamics of the adoption of e-commerce from a general perspective, products and services that have a different characteristic affecting the purchasing decision are ignored, and therefore, there could be a different adoption for each type of good or service marketed over the Internet in Colombia. However, how Colombians perceive the primary use of this commercial channel, i.e., as a tool, following the initial investigation of the technological adoption models has been identified.

5.4 Suggestions for future research

It is recommended for future research on the adoption of e-commerce in other countries to conduct cross studies between buyers and non-buyers so that they can provide successful solutions in the development of this channel for the entire population, especially in countries where the development of e-commerce is strongly conditioned by a digital gap [69, 48]. In addition, the use of the unified theory of technology adoption with the UTAUT model makes it possible to test other variables that were not taken into account in this study and that can provide a further description of the virtual consumer's behaviour; these may include the personality trait to innovations, the trait of buying low prices, and hedonic motivations, among other new factors that have been recently incorporated into technological adoption theories. It may also be interesting to conduct preliminary studies on groups of products and/or services purchased preferentially through this channel and to apply this model to find possible differences. Finally, this

study can be replicated in the near future to compare the behavioural changes in the adoption of e-commerce in this country through a longitudinal analysis.

Regarding the moderating effects discovered in an exploratory manner, it is necessary to examine whether they are similarly generated in other countries with the same level of e-commerce adoption or whether, instead, they have only been found in this study because it is possible that, in countries with a high development of e-commerce, the moderating effect of socioeconomic status may not be significant because the use of e-commerce is fairly extensive. The opposite occurs with the moderating effect of educational level because the results of this study have found that it is possible that the higher the educational level is, the higher the effects on the adoption of e-commerce in general. In addition, by having some relationships more greatly affected, future studies should test these hypotheses regarding their moderating effect with respect to social influence and performance expectations.

Annex 1. Measuring tool.

Construct	Item	Support literature
Buying Intention (BI)	BI1. I intend to use the Internet to buy something in the next few days	[37]
	BI2. In the future, I would buy something using the Internet	
	BI3. I prefer to shop using the Internet than traditional channels	
Performance expectations (PE)	PE1. In general, I think that buying online is very useful.	[66]
	PE2. In general, I think that buying online gives me advantages over traditional forms of purchase (physically in stores)	
	PE3. Overall, I think that buying on the Internet does not take a long time when I perform the operation.	
Effort expectations (EE)	EE1. In general, I think that buying online is easy and simple.	[40]
	EE2. In general, I think that buying online allows me to do it my way, and I am the one who manages the purchase (time, date, etc.)	
	EE3. In general, I think that buying online does not require a lot of learning.	
Social influence (SI)	SI1. The important people in my life, such as family and friends, recommend that I purchase online	[66]
	SI2. Other people I know (for example, my colleagues or bosses) recommend buying over the Internet.	
Facilitating conditions (FC)	FC1. I have what I need (computer, Internet access, credit card, debit card, or other means of payment, etc.) to make an online purchase.	[37]
	FC2. I have the knowledge to perform the entire buying process online (entering the web, browsing, shopping, and paying online)	
	FC3. Typically, on the websites where I buy, I have help or support	

	when there are problems during the purchase.	
Perceived risk (PR)	PR1. In general, I think that buying online is risky PR2. Overall, I think that paying by electronic means (credit and debit cards) is dangerous PR3. In general, I think that there is a possibility that buying over the Internet can generate problems with the outcome of the purchase	[42]

Source. The authors

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Implementation of elements of sustainability applied to the modernization of productive areas: Spain, a case of technological deficiency in southern Europe

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Abstract

The modernization of productive areas -industrial estates, technology and logistics parks, etc.-, involves the need to incorporate solutions that provide them with greater sustainability. The specificities of these areas, such as their high energy consumption or significant water intake, means that their implementation requires the adoption of measures that reduce the impact on the environment, contributing to the concept of a sustainable productive area. The implementation of renewable energies and Smart Grids, the improved water cycle and the introduction of robotics are solutions that enable making these spaces more sustainable in the field of infrastructures. This article analyses and verifies their implementation in a significantly important industrial area of Spain, ultimately concluding that such elements are scarcely implemented in productive areas.

Key words: productive area; urban infrastructure; sustainability; civil engineering.

Implantación de elementos de sostenibilidad aplicados a la modernización de áreas productivas: España, un caso deficitario en la Europa del sur

Resumen

La modernización de las áreas productivas -parques industriales, logísticos, tecnológicos, etc.-, comporta, desde la óptica urbanística, la oportunidad de incorporar soluciones que aporten una mejor sostenibilidad de las mismas. Las especificidades de dichos espacios, como son sus consumos energéticos elevados o las importantes necesidades de agua, hacen que su implantación requiera de la adopción de medidas que minoren la afectación sobre el medio ambiente, contribuyendo al concepto de área productiva sostenible. La introducción de las energías renovables y las Smart Grids, la mejora del ciclo del agua y la aplicación de la robótica son soluciones que en el ámbito de las infraestructuras urbanas permiten hacer más sostenibles estos espacios. El presente artículo analiza y comprueba su implantación en un entorno industrial significativamente relevante de España, concluyéndose como resultado final la escasa incorporación de dichos elementos en las áreas productivas.

Palabras clave: área productiva; infraestructuras urbanas; sostenibilidad; ingeniería civil.

1. Introducción

En el territorio español, la industrialización se produjo más tarde que en gran parte del territorio europeo, consecuencia de la inestabilidad económica y social producida por la guerra civil. Esta tardía industrialización provoca que las primeras áreas productivas, tal y como las

conocemos – *polígonos industriales* -, no aparezcan hasta la segunda mitad del siglo XX.

La configuración actual de las áreas productivas corresponde a un modelo que se ha repetido desde su creación, que, en parte (no para todos los sectores, no para todas las situaciones) está obsoleto en aspectos clave como su localización y los patrones de diseño y gestión, y que el

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deterioro de algunas de estas áreas se deriva de su propia concepción. De hecho, una buena parte de las iniciativas de regeneración de áreas productivas tienen por objetivo revertir el proceso de segregación y especialización, introduciendo funciones que incrementen la variedad de uso y la complejidad, demandando una vida más variada similar a la que ofrece la ciudad. [1]

Después de más de 50 años, las actuaciones de regeneración y rehabilitación de dichas áreas han sido escasas, observando en muchos casos un estado de deterioro y una falta de innovación urbanística. Esta dejadez hacia las áreas productivas, que, históricamente han sido instaladas en terrenos de bajo coste y condenadas al envejecimiento por su uso y desgaste, es un claro indicativo de la necesidad de modernización y regeneración de las mismas.

La necesaria modernización de las áreas productivas, presenta unas consideraciones especiales motivadas por sus requerimientos de funcionamiento. Desde la óptica de sus infraestructuras y redes de servicios se debe contribuir a que dichas implantaciones sean medioambientalmente sostenibles como cualquier otra actuación urbanística.

El proceso de regeneración de las áreas productivas es un proceso continuo y permanente en el tiempo, por lo que se pueden diferenciar los siguientes tipos de actuación [1]:

- Actualización / reurbanización: cuando se trata simplemente (o casi) de reconducir el estado del polígono a la situación inicial en cuanto a la funcionalidad de sus infraestructuras.
- Actualización / modernización: cuando se trata de subir el nivel del área industrial con mejoras de servicios, nuevas infraestructuras y una imagen renovada.
- Regeneración: cuando la intervención va más allá e implica transformaciones en la propia estructura del polígono y sus usos.
- Remodelación: cuando el área ha perdido su función original y es necesario la sustitución de usos.

Este artículo se centra en la modernización de las áreas productivas de manera que sean medioambientalmente más sostenibles y atractivas para las empresas y el consumidor. Teniendo en cuenta que la sostenibilidad en un área productiva se traduce en un retorno económico y/o una reducción en el impacto ambiental, además de la creciente concienciación social respecto al medio ambiente, hace que su aplicación en las áreas productivas no sea un tema trivial.

La modernización de las áreas productivas mediante la implantación de soluciones que mejoren la sostenibilidad, no sólo se produce por la incorporación de nuevas tecnologías, sino también por la incorporación de nuevos preceptos. Así por ejemplo, el uso del agua de lluvia para el riego de las zonas verdes es una cuestión conceptual y no viene condicionado por disponer de una tecnología especial, simplemente es un planteamiento que prioriza una inversión directa menor, resolviéndose en la mayoría de ocasiones desde la propia red de abastecimiento de agua.

Existe una gran diversidad de ejemplos donde se observan criterios de poca eficiencia, como el caso del funcionamiento del alumbrado público de sus calles durante toda la noche, cuando no circula ningún vehículo ni peatón, aludiendo a términos de seguridad; o el dimensionado de una canalización de drenaje para el agua que va a transportar una

vez cada 500 años, funcionando el resto del tiempo de manera incorrecta y sobredimensionada, comportando así una inversión excesiva al no contemplar alternativas de diseño conceptualmente adaptables a episodios de grandes crecidas.

Las consecuencias son muchas, todas ellas teñidas de despilfarro y de una inconsciente ignorancia de su alto coste en términos económicos y ecológicos. En definitiva, se ha caminado hacia un urbanismo contrario a los preceptos que marca el concepto de la sostenibilidad.

Se pueden establecer propuestas en la modernización de las redes de servicios a fin de maximizar su eficacia y contribuir a la mejora de la sostenibilidad de la urbanización, destacando por sus beneficios medioambientales [2]:

- Introducción de la generación de energías alternativas para autoconsumo del área productiva.
- Ahorro energético con niveles de iluminación diferenciados por espacios y horas.
- Reutilización de las aguas de lluvia.
- Tecnificación de las redes, a fin de mejorar la prestación de los servicios urbanos y la sostenibilidad social y medioambiental de estos servicios.

Estas propuestas permiten sentar las bases para un desarrollo urbanístico sostenible en la modernización de las áreas productivas [3], y es a partir de ellas que se ha comprobado el potencial de mejora en términos de sostenibilidad de las áreas productivas de España, y desde la óptica de las infraestructuras urbanas.

2. Metodología

La concreción de los diversos elementos de sostenibilidad posibles de introducir en las infraestructuras urbanísticas de las áreas productivas ha sido el punto de inicio del presente trabajo. Del conjunto de criterios de sostenibilidad que establece la metodología verde [4] – metodología que evalúa la reducción de los impactos del edificio y su emplazamiento por la implementación de medidas, tanto en estrategias de diseño como en factores de rendimiento-, se ha sintetizado la investigación en las medidas y estrategias referentes a la generación de energías renovables (Criterio B.11), y la retención de aguas de lluvia para su reutilización (Criterio C.15). Además, se ha estudiado la implantación de sistemas urbóticos que permiten una mejor gestión de las redes favoreciendo la eficiencia energética (Criterio B.9), el menor consumo de agua (Criterio C.14) y, una optimización de las redes.

Una vez determinados los elementos objeto de estudio para los diferentes tipos de actuación, se propone la comprobación de su implantación en las áreas productivas de España y por tanto el potencial de mejora de las mismas. Atendiendo al diseño de éstas y a la similitud de normativas existentes en el ámbito de las infraestructuras urbanas entre las distintas regiones y provincias, se ha elegido una muestra representativa de 20 áreas productivas - superficie total 600 ha.-, situadas en un entorno industrial con epicentro el Polígono Industrial Petroquímico de Tarragona -al sur de Barcelona-, el cual constituye el polo estratégico más importante de la industria petroquímica del sur de Europa.

La muestra se ha realizado de manera aleatoria y a partir de ella se han categorizado dichas áreas productivas según cuatro criterios:

- Naturaleza jurídica del promotor: público (ayuntamientos, administraciones regionales y empresas públicas), o privado (empresas promotoras y asociaciones de propietarios) La muestra consta de 11 áreas públicas y 9 áreas privadas.
- Tamaño de las superficies ocupadas clasificándose en tres tipos: áreas productivas grandes (>500.000 m²), medianas (entre 100.000 m² y 500.000 m²), y pequeñas (<100.000 m²). La muestra consta de 3 áreas grandes, 12 áreas medianas y 5 áreas pequeñas.
- Tamaño dominante de la subdivisión parcelaria: áreas con predominio de grandes parcelas (>6.000 m²), áreas con predominio de parcelas pequeñas (<6.000 m²) y áreas con disponibilidad de parcelas de superficies variadas (mixtas). La muestra consta de 8 parcelas pequeñas, 8 parcelas grandes y 4 parcelas mixtas.
- Distintas especializaciones en las actividades de las áreas productivas: polígonos industriales, parques tecnológicos, parques empresariales, etc. La muestra consta de 12 polígonos industriales, 1 parque tecnológico y 5 sectores de actividades económicas.

En algunos casos se ha detectado una transformación de la especialización prevista inicialmente con el paso del tiempo. Es el caso del Polígono Industrial de Constantí [5], donde la especialización inicial prevista para actividades logísticas, ha ido menguando y hoy en día dichas actividades no superan ya el 60 % del área.

El análisis se ha realizado comprobando las características de sus infraestructuras diseñadas a partir de la revisión de los proyectos técnicos de urbanización redactados en cada caso. Paralelamente se ha comprobado la realidad actual de dichas áreas: grado de ocupación, tipo de actividades que se desarrollan, grado de conservación y mantenimiento, calidad medioambiental, determinación del grado de uso de las infraestructuras que en su día se equipó cada área productiva, y por último, existencia de nuevas soluciones que hayan mejorado su sostenibilidad.

3. Elementos de sostenibilidad

Con el fin de conseguir que la implantación urbanística de las áreas productivas sea sostenible debe actuarse desde diversas vertientes del urbanismo. Concretamente desde la óptica de sus infraestructuras y redes de servicios, tanto en el diseño, funcionalidad y dimensionado de las redes, se pueden aportar soluciones de tipo tecnológico y conceptual que contribuyan a su sostenibilidad ambiental. Obtener un crecimiento económico sin perder de vista la protección del medio ambiente son las bases de la ecología industrial [6].

Este artículo estudia las estrategias que permiten reducir las emisiones de gases de efecto invernadero y a su vez generan un crecimiento económico. De entre el amplio rango de “mejoras sostenibles” se ha decidido focalizar la investigación en aquellas cuya instalación es viable en áreas productivas ya operativas, generan un crecimiento económico y generan una reducción considerable en la cantidad de gases emitidos. En concreto se ha estudiado la producción de energías renovables (solar y eólica), reaprovechamiento de agua y diversas medidas con relación a la eficiencia energética.

A lo largo del artículo se estiman las aportaciones medioambientales, en términos de kg de CO₂ no emitidos a la atmosfera, de todas las acciones estudiadas tomando como marco de referencia las condiciones ambientales de la zona (Tarragona).

3.1. Generación de energías renovables

Los problemas medioambientales, unidos al creciente precio del petróleo están derivando en un incremento en la producción y comercialización de energía limpia. La irrupción de las energías renovables, con un constante descenso en los costes, ha cambiado notablemente los flujos de energía en las redes eléctricas. Ahora los usuarios no sólo consumen sino que también producen electricidad a través de la misma red, por tanto, el flujo de energía es ahora bidireccional.

Paralelamente se está produciendo un continuo incremento de los costes de la energía eléctrica generada, transportada, distribuida y comercializada bajo el modelo tradicional, a la vez que se observa una voluntad de reducir el uso de combustibles sólidos y las emisiones de gases tóxicos. Esta situación queda reflejada en la Directiva 2009/28/CE y en la legislación de los países miembros, que establece el camino de la reducción de las emisiones tóxicas con el uso creciente de fuentes de energía renovables mediante la auto generación, en un marco de generación distribuida y autoconsumo, apoyado en la implantación de microrredes (Fig. 1), como pueden ser las que corresponderían a las implantadas en las áreas productivas. Aparece así el concepto de “Smart grid” una red inteligente puede ser definida como un sistema eléctrico que usa información bidireccional, tecnologías de comunicación seguras e inteligencia computacional de una manera integrada a través de todo el espectro del sistema de generación de energía hasta los puntos de consumo [7]. En términos de energía renovable, las Smart grids, se encargan en conectar la energía producida por fuentes renovables con la red eléctrica [8].

Existen diferentes alternativas para la generación de energía “in situ”. La instalación de paneles solares fotovoltaicos es una alternativa interesante en todas las zonas con una disponibilidad solar adecuada. En las áreas productivas es relativamente fácil aprovechando los múltiples espacios libres de uso general, como son las zonas

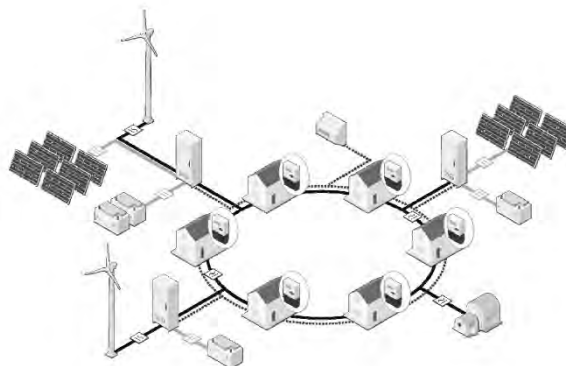


Figura 1. Esquema de una microrred.
Fuente: Tomado de [9].



Figura 2. Instalación eólica en el polígono industrial de Arinaga, Fuente: Tomado de [12].

de aparcamiento, las aceras (tipo pérgolas), o los espacios privados como son las cubiertas de las edificaciones. En las áreas productivas existen gran cantidad de espacios desaprovechados y de gran extensión que son adecuados para la implantación de estos sistemas.

La tecnología fotovoltaica permite la producción de entre 100 y 140 W/m² de energía [10]. Considerando la instalación de placas solares en un 10% de la superficie total del polígono y un factor de carga (porcentaje de tiempo en el cual el sistema funciona a lo largo de un año) del 20% (este factor de carga tiene en cuenta las horas nocturnas y los días no soleados), se genera un promedio de 2,4 kWh/km².

Esta producción de energía limpia, permite la no emisión de 0,72 kg de CO₂/(h·km²), aplicando un factor de emisión de 0,302 kg CO₂/kWh propuesto por la oficina catalana de cambio climático para la producción de energía eléctrica de carácter general [11].

Además de la energía solar, la energía eólica, en zonas climáticas adecuadas, es una buena alternativa con la instalación de turbinas eólicas en zonas verdes o espacios libres, como es el caso de la zona industrial de Arinaga –Canarias– (Fig. 2).

La instalación de generadores de electricidad por la acción del viento permite producir una gran cantidad de energía limpia en el área productiva, para el autoconsumo de los servicios comunes del polígono y de las empresas situadas en el mismo. La sustitución de las fuentes de energía convencionales por energía eólica reduce las emisiones asociadas a la producción de electricidad. La instalación de un molino de potencia 1.5 MW con factor de carga del 20% [13] se traduce en la no emisión de 90,60 kg CO₂/h. Además el impacto ecológico de estas instalaciones es muy bajo, al ubicarse en áreas industriales o de servicios.

La instalación de sistemas generadores de energía renovable es una posibilidad viable y sostenible en cualquier tipo de actuación independientemente del estado de las redes existentes, ya que se comportan como un complemento de las mismas.

3.2. Reutilización de las aguas de lluvia

Durante años la práctica habitual de drenaje urbano ha sido conducir el agua rápidamente fuera de las áreas desarrolladas. Los cauces urbanos han sido canalizados y las

alcantarillas diseñadas para recibir toda el agua de escorrentía superficial. Fruto de estas prácticas, los ríos han perdido su riqueza natural y su capacidad de respuesta ante las crecidas, mientras que los sistemas de alcantarillado se ven incapaces de absorber la cantidad de agua adicional procedente de las zonas de nuevo desarrollo urbano [14].

Frente a estos problemas surge el drenaje urbano sostenible. El agua de lluvia que cae sobre los espacios urbanizados es susceptible de reutilización puesto que se trata de agua no contaminada y fácil de recoger y conducir hacia el lugar escogido. Según las condiciones climáticas puede suponer una cantidad nada despreciable y, en todos los casos, permite el máximo aprovechamiento de un recurso valioso. Esta posibilidad conlleva beneficios tanto a nivel ecológico como a nivel paisajístico, puesto que puede utilizarse como herramienta de diseño y como instrumento de integración paisajística.

Se pueden identificar algunas opciones de reaprovechamiento de las aguas pluviales, compatibles entre sí (Fig. 3):

De todas las soluciones identificadas, cabe destacar por su interés para las áreas productivas los estanques de laminación y la infiltración superficial, pudiéndose concretar distintas soluciones técnicas [15]:

- Superficies permeables: sistemas constituidos por un volumen de material permeable situado bajo una superficie que permite el paso del agua pudiendo tratarse de césped, grava, pavimentos de bloques impermeables con huecos rellenos de césped o grava, pavimento de bloques porosos etc.
- Zanjas y depósitos de infiltración: perforaciones y trincheras rellenas de material granular que sirven para recoger y almacenar el agua de escorrentía hasta que se produce la infiltración de la misma al terreno natural (Fig. 4).

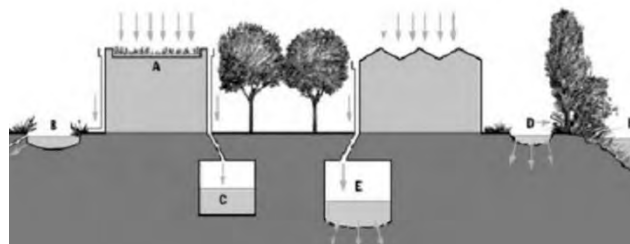


Figura 3. Esquema de reaprovechamiento de las aguas de lluvia [15]. A: Retención sobre cubierta, B: Estanque de laminación, C: Deposito de almacenamiento, D: Infiltración superficial, E: Infiltración subterránea, F: Evacuación sobre un curso fluvial.

Fuente: Tomado de [15].

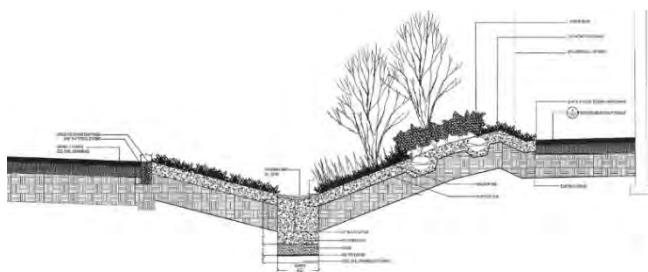


Figura 4. Propuesta de sistema de drenaje en zanja en Harvard University, Cambridge, Massachusetts

Fuente: Tomado de [15].



Figura 5. Depósito de retención en Lebario Industrie. Bolentin Deal, Rumania
Fuente: Elaboración Propia



Figura 6. Propuesta de sistema de drenaje en SW 12th Avenue Green Street, Portland, Oregon.
Fuente: Tomado de [16]

- Drenos filtrantes: zanjas recubiertas de geotextil y rellenas de grava dentro de las cuales circula el agua que proviene directamente de las superficies de drenaje de una tubería de aportación.
- Depósitos de laminación: depósitos que contienen un cierto volumen de agua de manera permanente, que es evacuado según necesidades a redes de evacuación o canales de riego (Fig. 5).
- Recogida de aguas de lluvia en superficies y creación de alcorques continuos con alimentación desde ellas (Fig. 6).

De la amplia variedad de alternativas existentes se deduce que cualquier tipo de superficie es susceptible de convertirse en un elemento recuperador de agua, las cunetas pueden ser de césped en lugar de hormigón, las zonas verdes pueden tener su estanque, cualquier franja de tierra se puede convertir en una franja filtrante. Tan sólo se necesita voluntad para obrar el cambio [17].

Las actuaciones relacionadas con el reaprovechamiento de agua son un caso especial en la rehabilitación de áreas productivas, ya que su viabilidad depende en gran medida del estado de las redes de recogida de agua, pudiéndose distinguir tres posibilidades:

- Red de evacuación de aguas unitaria y en buen estado: Este es el caso más desfavorable en cuanto a la instalación de acciones de reaprovechamiento de aguas. El hecho de que el agua, tanto pluvial como residual sea conducida por las mismas canalizaciones hace económicamente inviable la

actuación en este aspecto. La conversión de las redes de evacuación de aguas de un área industrial de unitaria a separativa es, a la práctica, casi imposible.

- Red de evacuación de aguas unitaria con necesidad de rehabilitación: En este caso, la necesidad de regeneración de la infraestructura, hace que la modificación del tipo de red de saneamiento se convierta en una alternativa. En estos casos, si se decide realizar el cambio en el tipo de red, la instalación de sistemas de recogida de agua es relativamente fácil.
- Red de evacuación de aguas separativa: La red separativa recoge las aguas “limpias” en una canalización separada, esto hace relativamente fácil la instalación de infraestructuras que permitan aprovechar el agua de lluvia en las áreas industriales.

El aprovechamiento de aguas pluviales permite reducir la huella ecológica del agua que se utiliza en el área productiva. El consumo energético estimado asociado al tratamiento de aguas pluviales es de 0.37 kWh/m^3 , mientras que el de aguas generales es de 2.5 kWh/m^3 [18], la recogida de agua de lluvia, genera una reducción en la cantidad de aguas generales que se han de tratar. Teniendo en cuenta las condiciones pluviales de la zona ($554,8 \text{ mm}$) [19], el reaprovechamiento de las aguas de lluvia se traduce en la no emisión de $0,04 \text{ kg/h de CO}_2$.

3.3. Urbótica

La aplicación de la urbótica –conjunto de las tecnologías de la electrónica, de los automatismos, de la informática y de las telecomunicaciones- en las áreas productivas permite ofrecer una mejora en el diseño y prestación de los servicios urbanos, una mejor sostenibilidad social y medioambiental de estos servicios y una gestión más eficiente de los mismos [20].

La urbótica plantea la extensión de las redes de comunicación de alta capilaridad y la implantación masiva de sensores y de actuadores, que a modo de sistema nervioso y utilizando como soporte físico el mobiliario urbano, el pavimento, el arbolado o cualquier otro elemento del espacio público, permiten incidir en la automatización y la gestión inteligente de los servicios urbanos. El resultado de la aplicación de los recursos urbóticos a las áreas productivas, haciendo un símil con la ciudad inteligente (Smart City, en la terminología anglosajona), comportaría lo que se podría denominar el área productiva inteligente (Smart Business Park).

Disponer de información en tiempo real y diferido, y de capacidad de actuación, mejora la gestión de los servicios estructurales y consigue reducir los costes de gestión y el impacto ambiental que estos generan. Redes de sensores, dispositivos de comunicación y una plataforma de gestión, forman el ecosistema tecnológico necesario para adquirir información de lo que está pasando en un entorno o espacio, almacenarla, y ponerla a disposición de gestores y usuarios mediante aplicaciones finales, existentes o de nueva creación, permitiendo actuar en tiempo real sobre el espacio urbano [21].

La aplicación de sistemas urbóticos de distribución de agua potable, electricidad y alumbrado público es aplicable a cualquier tipo de actuación independientemente del estado de

las redes del polígono en cuestión. Estos sistemas actúan como un complemento de la red, por lo que no tienen un coste de instalación elevado. Cabe hacer un comentario en los sistemas de recogida de aguas y la depuración de agua por métodos biológicos, que quedan exentos de este estudio, pero son un reto de futuro para los proyectos de nueva construcción o regeneración de áreas industriales.

3.3.1. Distribución de agua potable

El sistema de telemando y control en tiempo real (RTC) consigue un mejor funcionamiento de las instalaciones, ya que permite conocer las variables que informan del estado de la red (caudales, presiones, concentraciones de cloro libre, etc.) proporcionadas por instrumentación adecuada para garantizar su fiabilidad; conocer el estado de funcionamiento de los elementos y equipos integrados dentro de los centros de producción de agua potable y bombeo; modificar consignas de elementos que funcionen en modo automático; y maniobrar determinados elementos de operación de la red a distancia (válvulas, motores bombas, etc.).

Los datos captados en tiempo real de cada una de las estaciones remotas son recogidos, gestionados y visualizados en un Centro de Control. Además de la gestión propiamente dicha, la información obtenida permite su análisis en el caso de afecciones en el servicio; utilizar dicha información para la confección y actualización de modelos matemáticos de las redes de distribución de agua potable; realizar la gestión del mantenimiento; y asegurar la calidad y mejora continuada en la gestión de los procesos. La utilización de sistemas de lectura a distancia con utilización de contadores electrónicos que proporcionan datos extendidos es la opción que aporta un mayor valor añadido en los procesos de gestión de las redes de abastecimiento, ya que permite controlar de forma más eficiente el recurso del agua al permitir conocer cómo se realizan los consumos, así como optimizar el gasto que realizan los clientes ya que, por los datos aportados, se pueden detectar fugas y corregirlas rápidamente, fomentando el ahorro [22].

3.3.2. Suministro de energía eléctrica

El adecuado funcionamiento de las Smart Grids, viene dado por un control en tiempo real del consumo eléctrico de cada abonado, haciendo imprescindible la lectura de contadores de manera remota y transmitir esta información a un ordenador central. Para ello, es necesario disponer de contadores electrónicos que con sus funcionalidades aportan una serie de ventajas a la gestión de dichas redes: control remoto de consumo mediante el mismo cableado eléctrico que transmite la electricidad; actualización de firmware remota para incorporar nuevas funcionalidades; mayor número de parámetros medidos; control de la potencia demandada; y gestión de la conexión/desconexión del suministro, entre otras.

La utilización de contadores inteligentes permite a los consumidores recibir información sobre sus hábitos de consumo y el precio asociado de la electricidad. Con esta información, pueden modificar sus patrones de consumo, consumiendo en periodos de tiempo en los cuales el coste de la energía sea menor.

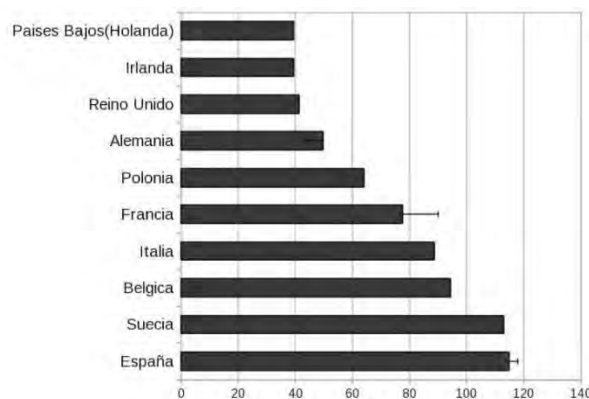


Figura 7. Gasto eléctrico en alumbrado público por habitante (kWh/año). Fuente: Tomado de [23]

Como consecuencia se espera un aumento en la eficiencia del uso de la energía, una reducción del pico de demanda (entre el 10 y 20 %), una reducción en la profundidad en los periodos de menos demanda, y un efecto positivo en la sostenibilidad mediante la reducción del coste y las emisiones de carbono [21], cuantificándose la no emisión en $0,15 \text{ kg CO}_2/(\text{h}\cdot\text{km}^2)$ [11].

3.3.3. Alumbrado público

Un aspecto muy importante a tener en cuenta en el diseño del alumbrado no solamente es el nivel de iluminación y la contaminación lumínica, sino también el coste de su mantenimiento, coste que ha tenido un valor creciente en los últimos años en España, siendo el mayor de los principales países de la Unión Europea, tal como se muestra en la Fig. 7.

La gestión mallada a distancia permite reducir la factura que se paga a la compañía suministradora en concepto de alumbrado público, consumiendo menos. A grandes rasgos consiste en instalar en cada farola un dispositivo que permite controlar la intensidad del alumbrado de cada punto de luz, bien de manera programada o en tiempo real, online. En el primer caso disminuiría en un porcentaje establecido a partir de cierta hora. Por ejemplo, a partir de medianoche las luminarias funcionarían al 40 % de su capacidad, con el consiguiente ahorro energético [24]. En el segundo, el control se ejercería desde un ordenador que permite que un operario controle directamente, en tiempo real, cada uno de los puntos de luz. Así podría reducirse en un momento determinado la intensidad luminosa de una farola y, al mismo tiempo, aumentar la de la que está justo al lado.

La reducción de potencia de las luminarias al 40% de su valor nominal en las horas nocturnas, se traduce en un ahorro de 0.5 kW/km^2 tomando como referencia un consumo típico de alumbrado urbano (50 W/m^2). Además la sustitución de las luminarias convencionales por nuevas luminarias tipo led causa una reducción en el consumo en un mínimo de 50%. El efecto medioambiental, no es trivial, ya que mediante la optimización energética del alumbrado público se puede reducir las emisiones en $0,26 \text{ kg CO}_2/(\text{h}\cdot\text{km}^2)$ (reducción de potencia), $0,52 \text{ kg CO}_2/(\text{h}\cdot\text{km}^2)$ (renovación de luminarias) o $0,64 \text{ kg CO}_2/(\text{h}\cdot\text{km}^2)$ (efecto combinado de la renovación de luminarias y la reducción de potencia).



Figura 8. Parque industrial IMM Slobozia (Rumania)
Fuente: Elaboración Propia

La aparición de nuevos tipos de lámparas, por ejemplo tipo LED, con mucho menor consumo y con la posibilidad de apagado-encendido inmediato, permiten nuevas posibilidades en este ámbito. Ya no es necesario que funcione el alumbrado toda la noche sino que puede tener apertura en el momento que se detecte la circulación de personas o coches por una calle, con el consiguiente ahorro efectivo e inmediato. Además, por los reducidos consumos de dichas lámparas se puede implementar su alimentación eléctrica a partir de placas fotovoltaicas instaladas en la propia columna o farola (Fig. 8).

4. Análisis y resultados

El análisis realizado se ha basado en la comprobación de la implantación de instalaciones de generación de energía renovable, la reutilización de las aguas grises y de lluvia, y en la implantación de sistemas urbóticos con fines de mejora de la sostenibilidad. Se han revisado los proyectos técnicos que en su día sirvieron de base para la ejecución de la obra, se ha comprobado el estado actual de sus infraestructuras, y el funcionamiento de cada área, obteniéndose los siguientes resultados:

4.1. Generación de energía renovable

En un 80% de las áreas productivas estudiadas existen instalaciones privadas de generación de energía renovable de origen fotovoltaico instaladas de manera mayoritaria en las cubiertas de las edificaciones, aunque con una potencia instalada irrelevante respecto a las necesidades totales. No hay ninguna instalación eólica a pesar de las buenas condiciones de viento de algunas de las localizaciones estudiadas. Por último tampoco se han aprovechado los espacios públicos para la implantación de estas instalaciones de generación de energía. De manera adicional, se ha detectado la producción de electricidad mediante pequeñas instalaciones de cogeneración en gran parte de los polígonos industriales analizados.

Cabe destacar, curiosamente, que las áreas productivas con implantación de instalaciones privadas de generación de energía renovable se mantienen, sin variaciones cuantitativas destacables o dignas de mención, en las categorizaciones que

se han establecido según la naturaleza jurídica del promotor, el tamaño de la actuación, el tamaño de la parcelación o la especialización del área productiva.

4.2. Reutilización de aguas grises y de lluvia

En este ámbito los resultados son totalmente negativos. No se ha encontrado ninguna área con algún tipo de aprovechamiento de las aguas grises o de lluvia, bien sea para riego, para abastecimiento de procesos productivos, limpieza de espacios, etc. En todos los casos las aguas grises son depuradas y llevadas a cauces de diversos tipos a igual que las aguas de lluvia. En un 15% de la muestra estudiada se han aplicado soluciones de infiltración de aguas de lluvia que permiten mantener una humidificación mínima del terreno.

4.3. Urbótica

Se dispone de sistemas urbóticos principalmente en la distribución de agua potable (60% de la muestra) con el telecontrol de las redes, y también en el alumbrado público mediante sistemas de reducción de consumo energético (100% de la muestra) basados en la reducción de flujo luminoso a partir de una determinada hora, aunque no se ha avanzado en el campo de la sustitución de luminarias con LED u otros sistemas de menor consumo y gestión más eficiente.

Por lo que afecta a los sistemas de telecontrol de redes de distribución de agua potable, estos no se vinculan con ninguna de las categorizaciones establecidas y es completamente aleatoria su implantación desde este punto de vista. No obstante sí se ha detectado su vinculación con las condiciones de urbanización exigidas por el municipio donde el área está situada territorialmente o por las compañías suministradoras.

No existen soluciones aplicadas a las redes de evacuación de aguas, a las redes de distribución de energía eléctrica. La instalación de fibra óptica como uno de los elementos de comunicaciones y apoyo a los sistemas urbóticos es inexistente.

El urbanismo de las áreas productivas ha de evolucionar para convertirlas en áreas autosuficientes y medioambientalmente sostenibles. Se han identificado mejoras en este ámbito, pero por el momento solo son actuaciones con una tasa de retorno evidente (placas fotovoltaicas, reducción de flujo luminoso).

En términos de sostenibilidad el potencial de mejora es muy elevado mediante actuaciones de modernización de las áreas industriales como la instalación de energías renovables, el reaprovechamiento del agua o los sistemas urbóticos de suministro de agua y electricidad. Iniciativas que abogan por la “neutralidad de carbono” estimulan los edificios de bajo consumo, eficiencia y producción de energías renovables. En un futuro próximo los edificios comenzaran a ser energéticamente autónomos [25]. Por su parte las empresas tienen que hacer un esfuerzo por lograr una optimización energética de sus procesos y apostar por la producción de energía limpia.

Existen gran cantidad de estrategias para reducir las emisiones de gases, cuantificándose en este artículo (apartado núm. 3 - *diversos valores indicados en cursiva*) la

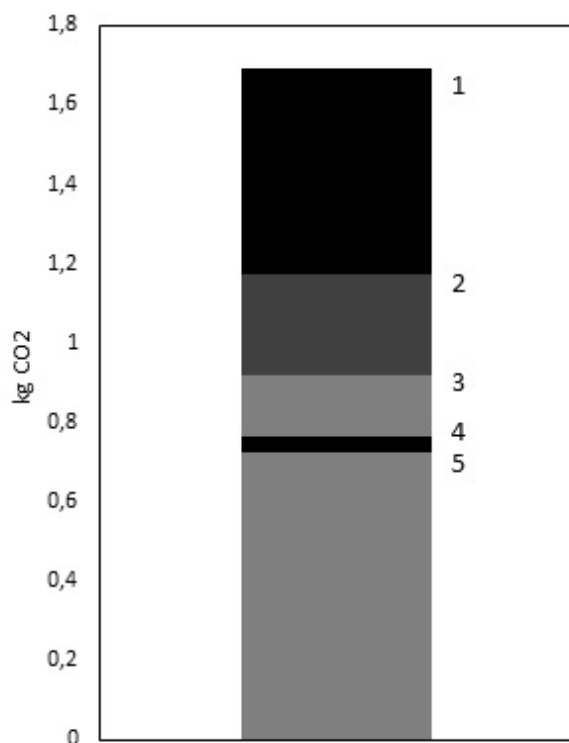


Figura 9. Reducción de emisiones de CO₂ para la sustitución de luminarias por luminarias led (1), reducción de la potencia de las luminarias (2), implantación de Smart grids (3), recuperación del agua de lluvia (4) e instalación de placas fotovoltaicas (5)

Fuente: Elaboración propia

reducción en emisiones (kgCO₂/(h·km²) producida por la instalación de placas fotovoltaicas (0,72), la instalación de turbinas eólicas (90,60), el aprovechamiento del agua de lluvia (0,04), la reducción de consumo en alumbrado público (0,26), la renovación del alumbrado público (0,52), y la implementación de redes inteligentes (0,15) tomando como referencia las condiciones climáticas de la zona objeto de estudio.

Considerando los valores del párrafo anterior se observa el alto potencial de mejora sostenible que tienen las áreas productivas de España (Fig. 9). La instalación de molinos eólicos se ha excluido de este gráfico debido a que la gran cantidad de electricidad que genera, hace que esta no pueda ser consumida exclusivamente por las áreas comunes del área industrial.

Por último volver a hacer especial hincapié en que no se han apreciado diferencias suficientemente significativas, en los resultados obtenidos de la muestra, en función de la naturaleza jurídica del promotor. Los resultados no son distintos entre las áreas productivas desarrolladas por instituciones públicas y las desarrolladas por instituciones privadas, pudiendo considerar esto un hecho especialmente relevante.

5. Conclusión

En España, los proyectos de urbanización de las áreas productivas, deben prever, de acuerdo a normativas

promulgadas básicamente en el periodo 1975 – 1980, las infraestructuras de pavimentación, red de abastecimiento de agua, red de alcantarillado, y red de distribución de energía eléctrica y alumbrado público.

Se constata que las áreas productivas se han diseñado con la previsión de estas infraestructuras obligatorias, funcionando, al cabo de años de estar operativas, de la misma manera que se diseñaron inicialmente, y no presentando ningún tipo de dinamismo en cuanto a la modificación y actualización respecto a las urbanizaciones originales, ya sea por nuevas necesidades o adaptación a cambios sociales o normativos.

A fin de mejorar la sostenibilidad de un área productiva, desde el ámbito de sus infraestructuras urbanas, existen soluciones técnicas contrastadas para cada una de las redes básicas (abastecimiento de agua, evacuación de aguas, red de distribución eléctrica y alumbrado público).

En algunos casos las soluciones técnicas son de tipo tecnológico y por tanto de aplicación reciente o futura, mientras que para otros casos son soluciones que siempre han sido aplicables pero que en la práctica se ha hecho poco uso de ellas, como es el caso de los depósitos de retención de aguas de lluvia para reducir dimensionado de canalizaciones de evacuación y a la vez aprovechar dichas aguas para otros usos.

El desarrollo o adaptación de infraestructuras, que permita una mejora de la sostenibilidad de las áreas productivas, se ha detectado como muy escaso. La mejora del ciclo del agua, la generación de energía renovable en las propias áreas, la instalación de alumbrado público con menos consumo eléctrico, la urbótica, etc., son aspectos que mediante su optimización permitirían mejorar las áreas desde el punto de vista de su funcionamiento y de mejora de la sostenibilidad, adaptándose a las nuevas realidades sociales y económicas que las empresas demandan.

En España, en general es necesario un proceso de puesta al día y mejora de las infraestructuras y de las condiciones medioambientales de las áreas productivas existentes, ya sea con el apoyo de la administración y/o de las empresas instaladas. De hecho son estas últimas, en definitiva, las que conocen los problemas del día a día y son ellas las primeras que deben ser conscientes de la importancia de tener un espacio moderno donde desarrollar la actividad económica que favorezca la aparición de economías externas.

Por último, cabe hacer una consideración sobre el concepto de espacio o área productiva actual, donde existen una serie de empresas que actúan de manera independiente, pagando unos gastos al municipio y a las empresas que explotan las redes quedando al margen completamente de los conceptos como el ahorro, la eficiencia o la sostenibilidad. La aplicación y adaptación de un concepto de gestión global de necesidades, donde todas las empresas instaladas puedan aprovechar esta nueva vertiente de sostenibilidad a modo de pequeñas Smart City, generando y consumiendo la energía eléctrica y vendiendo o comprando la sobrante en microrredes, aprovechando el agua de lluvia y la depuración de aguas grises, compartiendo servicios de vigilancia, y otros muchos servicios que se pueden hacer de manera mancomunada, permitiría mejorar rendimientos, reducir costes y convivir en un hábitat mucho más agradable.

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A 2-tuple linguistic multi-period decision making approach for dynamic green supplier selection

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Abstract

Green supplier selection aims to choose the best supplier, among several alternatives, taking into account not only traditional criteria such as cost and quality of service or product, but also considering the ability to produce these products or services fulfilling environmental standards or regulations and with the least negative impact on the environment. In real green selection contexts, sometimes a single static evaluation of suppliers is not enough for a conclusive decision and it is necessary to analyze suppliers' evolution throughout different moments. Obviously, some parameters are not constant over time, rather they are dynamic and change from one period to another. Consequently, decisions about suppliers take place in a dynamic environment, where the final decision is made after an exploratory process. Besides, the available information is vague or imprecise that does not involve probabilistic uncertainty. In such situations, the use of 2-tuple linguistic model provides a convenient way to represent linguistic assessments through linguistic variables and to model uncertainty. In this paper, the main focus is on finding the right supplier by using a multi-criteria multi-period decision making approach based on the 2-tuple linguistic computational model.

Keywords: Multi-criteria decision making; multi-period decision making; 2-tuple linguistic model; green supplier selection.

Un modelo de toma de decisión multiperíodo basado en 2-tupla lingüística para la selección dinámica de proveedores verdes

Resumen

La selección de proveedores verdes tiene como objetivo la elección del mejor proveedor, entre varias alternativas, teniendo en cuenta no solo criterios tradicionales como el costo y la calidad del servicio o producto, sino considerando también la capacidad de producir estos productos o servicios cumpliendo estándares o regulaciones ambientales y con el menor impacto en el medio ambiente. En contextos reales de selección verde, en ocasiones no basta con una única evaluación estática de los proveedores y se necesita considerar la evolución de los proveedores en diferentes momentos y por supuesto algunos parámetros no son constantes en el tiempo, más bien son dinámicos y varían de un período a otro. En consecuencia, las decisiones acerca de los proveedores tienen lugar en un entorno dinámico, donde la decisión final se toma luego de un proceso de exploración. Además, la información disponible es vaga o imprecisa que no implica la incertidumbre probabilística. En tales situaciones, el uso del modelo lingüístico 2-tupla proporciona una forma adecuada para representar las evaluaciones lingüísticas por medio de variables lingüísticas y modelar la incertidumbre. En este trabajo, la atención principal se centra en encontrar el proveedor adecuado utilizando un enfoque de toma de decisiones multicriterio y multiperíodo, basado en el modelo computacional 2-tupla lingüística.

Palabras clave: toma de decisión multicriterio; toma de decisión multiperíodo; modelo lingüístico 2-tuplas; selección de proveedores verdes.

1. Introduction

Since organizations and companies dedicated to projects development become increasingly dependent on suppliers, the effectiveness in decision making for suppliers selection

also becomes an essential success factor. Effective processes for supplier evaluation and selection directly impact supply chain performance and consequently organizational productivity and profitability. Some authors have identified as factors determining the complexity of supplier selection,

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the following [1,2]:

- 1) Combinations of different decision rules derived from the buying process internal and external constraints.
- 2) Multiple criteria, both qualitative and quantitative, that may be conflictive.
- 3) Involvement of many alternatives.
- 4) The number of decision makers.
- 5) The various types of uncertainty.

Ho et al. [3] found that quality, delivery, price/cost and manufacturing capability are the most popular conventional criteria for decision makers in evaluating and selecting the most appropriate supplier.

As many conflicting factors should be taken into account in the analysis, the supplier selection problem is usually modeled as a multi-criteria decision making (MCDM) problem in which it is necessary to select the best supplier(s) from a predefined set with respect to such conventional decision criteria [3-6].

Recently, there has been an increasing public awareness, government regulation and market pressure on sustainability issues. Companies may not neglect the role of environmental issues if they want to achieve better profit and remain in the market with competitive advantages [7]. This means that balancing the environmental performance with the reduction of time to respond to market demand, the products' cost, the quality improvement and the human resource management, have moved companies to search for better models to find their green suppliers [8,9]. Green supplier selection is generally intended to involve screening suppliers based on their environmental performance and doing business only with those that meet certain environmental regulations or standards. Integrating the green dimension in the resolution of supplier selection problems implies addressing the relationship between the suppliers evaluation and the natural environment, that is, the influence of the former on the latter.

To consider the environmental performance, different authors have proposed additional "green" attributes. Azzone and Bertele [10] include the external environmental benefit, the environmental benefit, the green image and the environmental adaptability. Similarly, Noci [11] proposed to consider the conformance to environmental specifications, the environmental benefit, the supplier's green image and net life cycle cost. Sarkis and Talluri [12] proposed the environmental design, the life cycle analysis, the comprehensive quality environmental management, the green supply chain and ISO14000 requirements. Lee et al. [13] considered the green image, the pollution control, the environment management, the green product and green competencies. More recently, Govindar et al. found [14] the environmental management system as the most widely considered criterion for green supplier evaluation and selection. Another novel concept is "the greening", introduced by Rao [15] including green marketing, green purchasing, green design, and green production.

The supplier selection is related both, to the definition and evaluation of the criteria, and to the variation of the criteria over time. In the real-world, some parameters such as prices, capacities, and demands are not constant over time, rather are dynamic and vary from period to period. Conventional and green criteria might vary over time, new ones might be

considered, or existing ones could turn into irrelevant in different market conditions. Therefore, assessments about suppliers are provided in a changeable environment where the final decision is taken at the end of some exploratory process, i.e., dynamic green supplier selection. In such cases, this valuable exploration of the problem can be performed throughout a multi-period MCDM (MPMCDM) approach, also called dynamic MCDM. Its basic idea is that the input arguments (decision information) are usually collected from different periods and are all considered in the output (final decision) [16,17].

Additionally, sometimes due to the complexity and uncertainty of the green supplier evaluation process and the ambiguity of human thinking, experts face objective and subjective limitations to accurately measure the decision attributes. The available information about suppliers is often vague or imprecise, implying non-probabilistic uncertainties. Hence, the attribute values given by the experts cannot be assessed by means of numerical values because of time pressure, personal preferences, lack of knowledge or nature of attributes. In such situations, the use of the fuzzy linguistic approach provides a direct way to manage the uncertainty and model the linguistic assessments by means of linguistic variables. One of the suggested approaches for dealing with linguistic information is the 2-tuple linguistic representation model [2] which can improve the interpretability and usability of the decision making output while prevents loss of information in computations.

The 2-tuple linguistic model has received many attentions in theoretical and practical aspects and significant advances have been made in the research on time independent information aggregation [18-26], which are effective to aggregate the 2-tuple linguistic information collected in a single period. However, researches on 2-tuple linguistic MPMCDM are few [18]. How to aggregate the 2-tuple linguistic decision information collected at different periods and how to tackle the MPMCDM problems with 2-tuple linguistic information are still very interesting and meaningful research topics. Therefore, it is necessary to pay attention to these issues.

The aforementioned analyses lead to the following motivations of this work:

- Taking advantage of the 2-tuple linguistic representation model to make the proposed method has the strengths of modeling the uncertainty in supplier selection process as well as increasing the understandability and intuitiveness of its results expressed in linguistic terms.
- Improving and extend the 2-tuple linguistic model by introducing new 2-tuple linguistic dynamic aggregation operators.
- Combining the advantages of both 2-tuple linguistic model and the MPMCDM, and proposing a more powerful green supplier selection approach able to deal with more complex and dynamic evaluation situations which require gathering the uncertain decision information about suppliers in multiple periods.

There are diverse studies on supplier selection [1,3,6] and green approaches [14] that summarize the different solving methods including data envelopment analysis, cluster analysis, case-based-reasoning systems, decision models for

the final choice-phase, linear weighting models, total cost of ownership models, mathematical programming models, statistical models and artificial intelligence based models. Most of these approaches in the literature, employ qualitative or/and quantitative valuations collected in a single decision moment to determine the performance of the supplier. However, some practical applications would benefit from the adoption of an iterative process for considering the evolution of suppliers over time. The approach herein proposed addresses this gap by using as basis a MPMCDM model which enables a more realistic representation of the dynamism of supplier evaluation rather than a static picture of the behavior of suppliers at any given time.

Moreover, the use of 2-tuple linguistic representation allows multiple advantages: first, to model the uncertainty inherent in the selection process; second, to manage and integrate multiple linguistic opinions without any loss of information due to the aggregation operations are performed in a continuous domain; and third, to obtain without approximation processes, linguistic results with a higher level of interpretability than simple numbers.

The rest of the paper is structured as follows. Section 2 reviews in short the 2-tuple representation model. Section 3 develops some 2-tuple linguistic time dependent aggregation operators. Section 4 introduces the dynamic supplier selection model based on 2-tuple linguistic MPMCDM approach using these operators. In Section 5 a calculation example is pulled into to illustrate the feasibility of our dynamic supplier selection model from the empirical perspective and Section 6 concludes the paper.

2. Preliminaries on the 2-Tuple Representation Model

In this section, basic notions of the 2-tuple linguistic representation model are revised since it is the basis of our proposal to support decision processes in green supplier selection.

The 2-tuple linguistic model [27] aimed to improve the accuracy and facilitate the processes of computing with words by treating the linguistic domain as continuous but keeping the linguistic basis (syntax and semantics). It extended the use of indexes modifying the fuzzy linguistic approach by adding a new parameter, so-called symbolic translation.

Definition 1 [27] The symbolic translation is a numerical value assessed in $[-0.5, 0.5]$ that supports the “difference of information” between a counting of information β assessed in the interval of granularity $[0, g]$ of the linguistic term set S , and the closest value in $\{0, \dots, g\}$ which indicates the index of the closest linguistic term in S .

Fig. 1 shows how the symbolic translation value α represents the information difference between the aggregation result β and the index of the closest linguistic term s_i . This representation model defines the functions Δ and Δ^{-1} to facilitate the CWW processes [27].

Definition 2 [27] Let $S = \{s_0, \dots, s_g\}$ be a set of linguistic terms and $\beta \in [0, g]$ a value supporting the result of a symbolic aggregation operation. A 2-tuple linguistic value that expresses the equivalent information to β is obtained by the function $s_i: [0, g] \rightarrow \tilde{S}$ as follows.

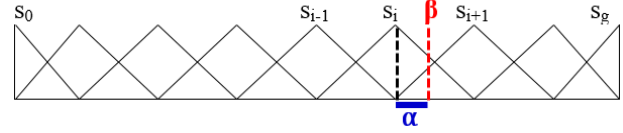


Figure 1. The symbolic translation to CWW processes.
Source: Adapted from [27].

$$\Delta(\beta) = (s_i, \alpha), \text{ with } \begin{cases} i = \text{round}(\beta) \\ \alpha = \beta - i \end{cases} \quad (1)$$

Being round the round operation, i the index of the closest label s_i , to β and α the symbolic translation. We note that Δ is a bijective function and $\Delta^{-1}: \tilde{S} \rightarrow [0, g]$ is defined by $\Delta^{-1}(s_i, \alpha) = i + \alpha$.

When dealing with linguistic information represented by 2-tuples, 2-tuple aggregation operators are logically required to accomplish computations and solve the MPMCDM problem. Functions Δ and Δ^{-1} in the fuzzy linguistic representation model with 2-tuples transform numerical values into a 2-tuples and viceversa without loss of information, therefore, conventional numerical aggregation operator can be easily extended for dealing with linguistic 2-tuples [27]. Based on this idea, several 2-tuple time independent aggregation operators have been developed [18-26]. Basic classical operators are the one revised here:

Definition 3 [27] Let $X = \{(s_1, \alpha_1), \dots, (s_m, \alpha_m)\}$ be a set of 2-tuple linguistic values, and $W = (w_1, \dots, w_m)$ the weighting vector such that $\sum_{i=1}^m w_i = 1$ the weighted averaging aggregation operator associated with W is the function $2TWM: \tilde{S}^m \rightarrow \tilde{S}$ defined as:

$$2TWM(X) = \Delta \left(\sum_{i=1}^m w_i \Delta^{-1}(s_i, \alpha_i) \right) \quad (2)$$

Epecially, if $W = \{\frac{1}{m}, \frac{1}{m}, \dots, \frac{1}{m}\}$, the 2TWA operator reduces to the 2-tuple arithmetic mean (2TAM) operator:

$$2TAM(X) = \Delta \left(\frac{1}{m} \sum_{i=1}^m \Delta^{-1}(s_i, \alpha_i) \right) \quad (3)$$

Since multiple decision problems take place in an environment that changes over time, it is important to consider the time dimension to model and solve the problems. Liu et al. [28] extended the 2-tuple weighted average operator to deal with time dependent or dynamic information.

Definition 4 [28] Let $X = \{(s_1, \alpha_1)^{(t_1)}, \dots, (s_q, \alpha_q)^{(t_q)}\}$ be a collection of q 2-tuple arguments collected from q different periods $T = \{(t_\lambda) | \lambda \in (1, \dots, q)\}$, whose weights are given by the weighting vector W^T , then the function $2TDWA: \tilde{S}^q \rightarrow \tilde{S}$ defined as:

$$2TDWA(\tilde{X}) = \Delta \left(\sum_{\lambda=1}^q w^{(t_\lambda)} \Delta^{-1}(s_i, \alpha_i)^{(t_\lambda)} \right) \quad (4)$$

is called a 2-tuple Dynamic Weighted Averaging aggregation operator, 2TDWA. Especially, if $W^T = \{\frac{1}{q}, \frac{1}{q}, \dots, \frac{1}{q}\}$, the TDWA operator reduces to the TDA operator:

$$2TDAM(\tilde{X}) = \Delta \left(\frac{1}{q} \sum_{\lambda=1}^q \Delta^{-1}(s_i, \alpha_i)^{(t_\lambda)} \right) \quad (5)$$

3. New 2-tuple time dependent aggregation operators

In order to deal with more complex and dynamic aggregation environments, in what follows, based on the Liu et al. [28] idea, new 2-tuple time dependent aggregation operators will be defined.

Definition 5 Let $X = \{(s_1, \alpha_1)^{(t_1)}, \dots, (s_q, \alpha_q)^{(t_q)}\}$ be a collection of q 2-tuple arguments collected from q different periods, $T = \{(t_\lambda) | \lambda \in (1, \dots, q)\}$, whose weights are given by the weighting vector W^T , then the function $2TDWG: \tilde{S}^q \rightarrow \tilde{S}$ defined as:

$$2TDWG(\tilde{X}) = \Delta \left(\prod_{\lambda=1}^q (\Delta^{-1}(s_i, \alpha_i)^{(t_\lambda)})^{w^{(t_\lambda)}} \right) \quad (6)$$

is called a 2-tuple Dynamic Weighted Geometric aggregation operator, 2TDWG.

Especially, if $W^T = \{\frac{1}{q}, \frac{1}{q}, \dots, \frac{1}{q}\}$, the 2TDWG operator reduces to the TDA operator:

$$2TDG(\tilde{X}) = \Delta \left(\prod_{\lambda=1}^q (\Delta^{-1}(s_i, \alpha_i)^{(t_\lambda)})^{\frac{1}{q}} \right) \quad (7)$$

Definition 6 Let $X = \{(s_1, \alpha_1)^{(t_1)}, \dots, (s_q, \alpha_q)^{(t_q)}\}$ be a collection of q 2-tuple arguments collected from q different periods, $T = \{(t_\lambda) | \lambda \in (1, \dots, q)\}$, whose weights are given by the weighting vector W^T , then the function $2TDOWA: \tilde{S}^q \rightarrow \tilde{S}$ defined as:

$$2TDOWA(\tilde{X}) = \Delta \left(\sum_{\lambda=1}^q w^{(t_\lambda)} \Delta^{-1}(s_j, \alpha_j)^{(t_\lambda)} \right) \quad (8)$$

is called a 2-tuple Dynamic Ordered Weighted Averaging aggregation operator, 2TDOWA, where (s_j, α_j) is the j -th largest of the $(s_i, \alpha_i)^{(t_\lambda)}$ values.

Definition 7 Let $X = \{(s_1, \alpha_1)^{(t_1)}, \dots, (s_q, \alpha_q)^{(t_q)}\}$ be a collection of q 2-tuple arguments collected from q different periods, $T = \{(t_\lambda) | \lambda \in (1, \dots, q)\}$, whose weights are given by the weighting vector W^T , then the function

2TDOWG: $\tilde{S}^q \rightarrow \tilde{S}$ defined as:

$$2TDOWG(\tilde{X}) = \Delta \left(\prod_{\lambda=1}^q (\Delta^{-1}(s_j, \alpha_j)^{(t_\lambda)})^{w^{(t_\lambda)}} \right) \quad (9)$$

is called a 2-tuple Dynamic Ordered Weighted Geometric aggregation operator, 2TDOWG, where (s_j, α_j) is the j -th largest of the $(s_i, \alpha_i)^{(t_\lambda)}$ values.

As a matter of fact, one key aspect in handling the MPMCDM problem with time dependent aggregation operators is to determine the period weighting vector. It can be given by decision maker(s) directly or it can also be computed by other methods.

4. Dynamic supplier selection based on 2-tuple linguistic MPMCDM approach

In this section we consider the 2-tuple linguistic multi-period approach for solving dynamic supplier selection problems, in which all the attribute values, provided by multiple experts at different periods, take the form of linguistic variables.

A dynamic supplier selection problem with linguistic assessments can be described as follows: Let $T = \{(t_\lambda) | \lambda \in (1, \dots, q)\}$, a discrete set of q periods. At every period $A^{(t_\lambda)} = \{a^{(t_\lambda)} | i \in (1, \dots, m)\}$, be a set of suppliers and $E^{(t_\lambda)} = \{e^{(t_\lambda)} | k \in (1, \dots, p)\}$ be the set of experts assessing the suppliers according to the set of criteria $C^{(t_\lambda)} = \{c^{(t_\lambda)} | j \in (1, \dots, n)\}$ whose weights are given by the weighting vector $W^{(t_\lambda)} = (w^{(t_\lambda)} | j \in (1, \dots, n))$. The preference provided by expert $e_k \in E^{(t_\lambda)}$ about supplier $a_k \in A^{(t_\lambda)}$ according to criterion $c_k \in C^{(t_\lambda)}$ is represented by a linguistic term $x_{ijk}^{(t_\lambda)}$.

To get the best supplier(s), we now develop an approach based on applying 2-tuple linguistic dynamic aggregation operators to linguistic MPMCDM. The main decision flowchart is depicted in Fig. 2. In summary, the proposed approach is composed by five steps.

We want to remark that Steps 1 to 3 aim to decompose the dynamic supplier selection problem into a set of conventional simple problems, corresponding to the q periods considered in the holistic problem. In this iterative way, in Step 1, 2-tuple linguistic matrices are constructed from the simple linguistic judgments provided by experts; in Step 2, these 2-tuple linguistic matrices are aggregated in order to obtain a collective value for each criterion; and in Step 3 the resulting matrices are aggregated to obtain the collective value for each supplier in one single period. If the exploratory procedure is extended to a new period, Steps 1 to 3 are executed again. At the end of this repetitive analysis, Step 4 is the final aggregation phase that computes a dynamic collective assessment for each supplier. To do this, time-dependent aggregation operators should be used. Finally, in Step 5 the dynamic collective assessments are ranked to choose the best supplier among the alternative ones.

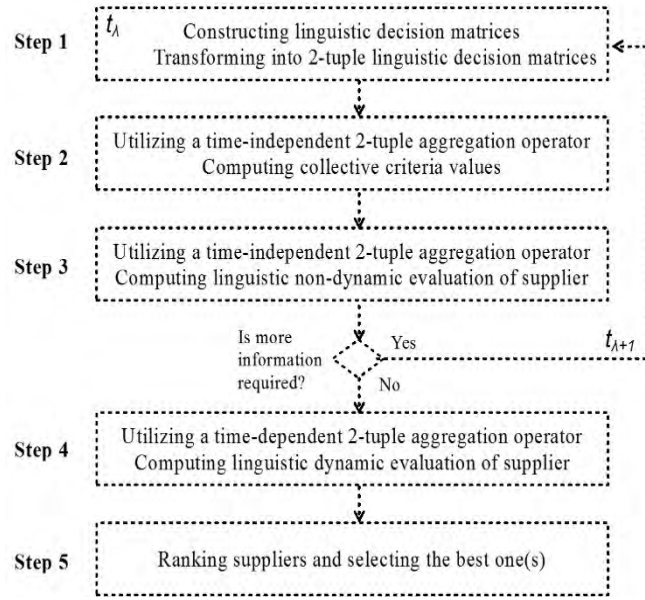


Figure 2. The flowchart for the linguistic MPMCDM approach to dynamic supplier selection.

Source: The authors.

Step 1: Constructing the linguistic decision matrices $(X^{(t_\lambda)})_{m \times n}$ and transforming them into linguistic 2-tuple decision matrices.

$$(\tilde{x}_i^{(t_\lambda)})_{m \times n} = (\tilde{x}_{ijk}^{(t_\lambda)})_{m \times n} = ((s, \alpha)_{ijk}^{(t_\lambda)})_{m \times n} \quad (11)$$

The conversion of a linguistic term s_x into a linguistic 2-tuple $(s_x, 0)$ consists of adding a value 0 as symbolic translation due to $\alpha=0$ represents no difference from the original value β to the transformed index x .

Step 2: Utilizing a classical 2-tuple aggregation operator and the weighting vector W_c for computing a collective value for each criterion for each period.

$$(\dot{x}^{(t_\lambda)})_{m \times n} = (\dot{x}_{ij}^{(t_\lambda)})_{m \times n} = Y(\tilde{x}_{ijk}^{(t_\lambda)}) \quad (12)$$

Step 3: Utilizing a classical 2-tuple aggregation operator for computing non-dynamic evaluation for each supplier for each period.

$$(\ddot{x}^{(t_\lambda)})_{m \times n} = (\ddot{x}_i^{(t_\lambda)})_m = \Psi(\dot{x}_{ij}^{(t_\lambda)}) \quad (13)$$

Step 4: Utilizing one of the 2-tuple Time Dependent (2TTD) aggregation operators introduced in Section 3 for computing dynamic evaluation for each supplier, if no other period will be considered in the multi-period exploratory process.

$$(\ddot{x}^{(t_\lambda)})_{m \times n} = (\ddot{x}_i^{(t_\lambda)})_m = 2TTD(\ddot{x}_i^{(t_\lambda)}) \quad (14)$$

The aggregation operators applied in Steps 2 to 5 are not inter-dependent or correlated and the selection is determined

by the characteristics of the supplier selection problem and the needs of decision makers.

Step 5: Ranking suppliers in accordance with $\ddot{x}_i^{(t_\lambda)}$ values and selecting the most desirable one(s).

Let us suppose two 2-tuple linguistic values, (s_k, α_1) and (s_l, α_2) , the comparison is as follows:

- if $k < l$ then $(s_k, \alpha_1) < (s_l, \alpha_2)$.
- if $k = l$ then
 - if $\alpha_1 = \alpha_2$ then $(s_k, \alpha_1) = (s_l, \alpha_2)$;
 - if $\alpha_1 < \alpha_2$ then $(s_k, \alpha_1) < (s_l, \alpha_2)$;
 - if $\alpha_1 > \alpha_2$ then $(s_k, \alpha_1) > (s_l, \alpha_2)$.

5. Illustrative Example

To better understand how the linguistic MPMCDM approach can be applied to the dynamic supplier selection problem, we now work through a small illustrative example. The main objective here is the selection of best supplier in a dynamic environment, for an organization dedicated to projects development. For simplicity, we consider a fixed set of four suppliers $A = \{a_1, a_2, a_3, a_4\}$. The attributes which are considered here in selection of the four possible suppliers are:

- Green capability (c_1): The ability to prepare, produce and deliver green products based on environmental standards.
- Price (c_2): The total cost of products offered as the price.
- Environmental management system (c_3): Applying any environmental management systems.
- Green design (c_4): A systematic method to reduce the environmental impact of products and processes.

Three experts provide assessment information on C in order to prioritize suppliers with respect to their green performance. In the following we utilize the method developed and give some calculation results to select the appropriate supplier.

Step 1: Experts use the linguistic term set: $S = \{s_0: \text{Extremely Low (EL)}, s_1: \text{Very Low (VL)}, s_2: \text{Low (L)}, s_3: \text{Medium (M)}, s_4: \text{High (H)}, s_5: \text{Very High (VH)}, s_6: \text{Extremely High (EH)}\}$, to provide evaluation information for suppliers in three moments according to the four attributes and construct, respectively, the linguistic decision matrices $(X^{(t_\lambda)}) = (X^{(t_\lambda)})_{4 \times 4}$ as listed in Table 1. Fig. 3 illustrates the structure and membership functions of each term in the linguistic set.

Step 2: For computing, collective criteria values for suppliers the 2TAM aggregation operator from Definition 3 is used. Results are listed in Table 2 and illustrated in Fig. 4.

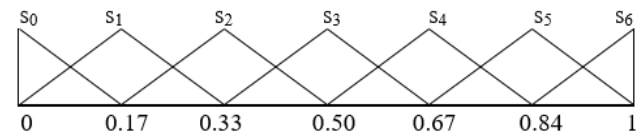


Figure 3. The structure of a linguistic set with seven terms.

Source: The authors.

Table 1.
Linguistic decision preferences for the five periods.

Period	Expert	Alternative	Criterio			
			c1	c2	c3	c4
t1	e1	a1	H	VL	H	VH
		a2	H	H	VL	M
		a3	VL	VH	EH	M
		a4	M	VH	L	M
	e2	a1	H	L	VH	M
		a2	H	H	L	VL
		a3	VL	M	VH	VH
		a4	L	EL	M	L
	e3	a1	M	M	H	VH
		a2	VH	L	EL	M
		a3	M	L	H	H
		a4	EH	H	EH	H
t2	e1	a1	VL	L	VH	M
		a2	M	M	VH	VL
		a3	H	M	H	VL
		a4	M	VH	H	M
	e2	a1	L	VL	EH	L
		a2	L	H	VH	VH
		a3	L	VL	VH	VL
		a4	L	EH	L	VH
	e3	a1	L	M	EH	H
		a2	EH	EL	VL	M
		a3	EH	EL	M	L
		a4	H	VH	H	H
t3	e1	a1	EH	H	M	VH
		a2	EL	EH	M	M
		a3	M	L	EH	VH
		a4	L	M	L	H
	e2	a1	M	VL	VL	M
		a2	H	H	H	H
		a3	VH	VH	H	L
		a4	L	M	EH	L
	e3	a1	H	M	L	M
		a2	M	VH	L	L
		a3	VH	VH	EH	H
		a4	H	L	VH	M
t4	e1	a1	VH	L	H	L
		a2	VH	H	H	VL
		a3	H	H	VH	M
		a4	M	VL	H	L
	e2	a1	VL	L	VH	M
		a2	VH	L	L	L
		a3	VH	EL	L	VL
		a4	M	H	M	M
	e3	a1	L	L	M	VH
		a2	H	M	VH	L
		a3	L	VL	M	VH
		a4	VH	VH	VH	M
t5	e1	a1	VH	L	H	L
		a2	VH	H	H	VL
		a3	VL	L	L	VL
		a4	M	VH	H	H
	e2	a1	M	L	VL	L
		a2	H	VH	L	VH
		a3	M	L	EL	M
		a4	H	VH	EH	VH
	e3	a1	L	L	M	VH
		a2	H	M	VH	L
		a3	L	VL	M	EL
		a4	VH	VH	VH	H

Source: The authors.

Table 2.
Collective criteria values for the five periods.

Period	Alternative	Criterio			
		c1	c2	c3	c4
t1	a1	(H,-0.33)	(L,0)	(H,0.33)	(H,0.33)
	a2	(H,0.33)	(M,0.33)	(VL,0)	(L,0.33)
	a3	(L,-0.33)	(M,0.33)	(VH,0)	(H,0)
	a4	(H,-0.33)	(M,0)	(H,-0.33)	(M,0)
t2	a1	(L,-0.33)	(L,0)	(EH,-0.33)	(M,0)
	a2	(H,-0.33)	(L,0.33)	(H,-0.33)	(M,0.33)
	a3	(H,0)	(VL,0.33)	(H,0)	(L,-0.33)
	a4	(M,0)	(VH,0.33)	(M,0.33)	(H,0)
t3	a1	(H,0.33)	(M,-0.33)	(L,0)	(H,-0.33)
	a2	(L,0.33)	(VH,0)	(M,0)	(M,0)
	a3	(H,0.33)	(H,0)	(VH,0.33)	(H,-0.33)
	a4	(M,-0.33)	(M,-0.33)	(H,0.33)	(M,0)
t4	a1	(M,-0.33)	(L,0)	(H,0)	(M,0.33)
	a2	(VH,-0.33)	(M,0)	(H,-0.33)	(L,-0.33)
	a3	(H,-0.33)	(L,-0.33)	(M,0.33)	(M,0)
	a4	(H,-0.33)	(M,0.33)	(H,0)	(M,-0.33)
t5	a1	(M,0.33)	(L,0)	(M,-0.33)	(M,0)
	a2	(H,0.33)	(H,0)	(H,-0.33)	(M,-0.33)
	a3	(L,0)	(L,-0.33)	(L,-0.33)	(VL,0.33)
	a4	(H,0)	(VH,0)	(VH,0)	(H,0.33)

Source: The authors.

Table 3.
Non-dynamic evaluation of suppliers for each period.

t	a1	a2	a3	a4
t1	(H,-0.42)	(M,-0.25)	(H,-0.50)	(M,0.33)
t2	(M,0.08)	(M,0.25)	(M,-0.25)	(H,-0.08)
t3	(M,-0.17)	(M,0.33)	(H,0.33)	(M,0.17)
t4	(M,0)	(M,0.25)	(M,-0.08)	(M,0.42)
t5	(M,-0.25)	(H,-0.33)	(L,-0.33)	(VH,-0.42)

Source: The authors.

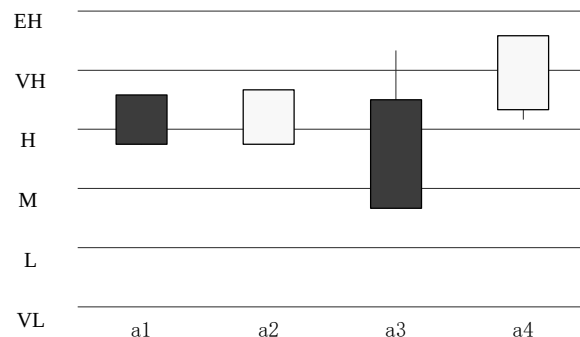


Figure 4. Plot of non-dynamic evaluation of suppliers.
Source: The authors.

Step 3: For computing, non-dynamic evaluation for each supplier the 2TAM is used as in the previous step. Results are listed in Table 3 and illustrated in Fig. 4.

Table 4.
Dynamic evaluation of suppliers using different aggregation operators.

AGOP	a1	a2	a3	a4
2TDA	(M,0.21)	(M,0.15)	(M,0.38)	(M,0.46)
2TDG	(M,0.11)	(M,0.24)	(M,-0.11)	(H,-0.35)
2TDWA	(M,0.03)	(M,0.34)	(M,-0.14)	(H,-0.22)
2TDWG	(M,0.02)	(M,0.33)	(M,-0.31)	(H,-0.26)
2TDOWA	(M,0.20)	(M,0.16)	(M,0.21)	(H,-0.42)
2TDOWG	(M,0.19)	(M,0.15)	(M,0.11)	(H,-0.44)

Source: The authors.

Table 5.
Ranking obtained by applying the comparison rules for 2-tuples.

AGOP	Ranking
2TDA	$a_4 > a_3 > a_1 > a_2$
2TDG	$a_4 > a_2 > a_1 > a_3$
2TDWA	$a_4 > a_2 > a_1 > a_3$
2TDWG	$a_4 > a_2 > a_1 > a_3$
2TDOWA	$a_4 > a_3 > a_1 > a_2$
2TDOWG	$a_4 > a_1 > a_2 > a_3$

Source: The authors.

Step 4: The dynamic evaluation for each supplier, is computed for these examples using several dynamic aggregation operators introduced in Section 3. For 2TDWA and 2TDWG the weighting vector for periods is $W^T = (0.1, 0.3, 0.6)$ while in contrast for 2TDOWA and 2TDOWG the weighting vector for periods is $W^T = (0.6, 0.3, 0.1)$. Dynamic evaluations of suppliers are illustrated in Table 4.

Step 5: The order of suppliers is obtained by applying the comparison rules for 2- tuples as shown in Table 5. The different aggregation operators produce different ranking and consequently different best suppliers.

6. Conclusions

Environmental laws and green production have become significant issues and in competitive markets, companies are required to implement green management practices. In order to process uncertain and dynamic information as precise as possible, and motivated by the idea of 2-tuple linguistic variables, we defined a new linguistic MPMCDM approach for dynamic green supplier selection.

The main advantage of this model is that it can assess uncertain situations with linguistic information provided in different gathering assessment moments due to the final decision requires an exploratory multi-period process in which some parameters vary from one period to another. In this way, it gives a more complete view of the dynamic green supplier selection problem to the decision maker because it considers several 2-tuple linguistic time-dependent aggregation operators. Therefore, the decision maker will use the particular case that is in accordance with his/her interests. The proposed MPMCDM approach allows experts to use linguistic assessment based on their expertise and research background. In this way, they can express their judgments more realistically and accurately and the final results are more reasonable, reliable and closer to the common model of communication of people.

For future research we believe that the evaluation framework can be improved by including not only linguistic

terms but also other information domains such as numbers, interval-values and linguistic expressions. A heterogeneous evaluation framework allows modeling the hesitancy and uncertainty in qualitative and quantitative contexts, in a more suitable and flexible manner.

In addition, it would be very interesting to extend our analysis to the case of more sophisticated green supplier situations. This may help to identify other complex decision issues such as the interaction between green criteria and the relative importance of each period in the final result.

In general, the proposed method can solve 2-tuple linguistic MPMCDM problems. Thus, it can be used to supplier selection and other similar evaluation problems.

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First approach to unilateral transfemoral amputees' contact mechanics

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Abstract

The stresses in the hip area have great importance because of their relationship to the health of the joint. Finite element models can predict contact between cartilages, however, contact patterns in unilateral transfemoral amputees have not yet been found in literature. We thus want to present an initial approach in the contact mechanics of the hip joint of these amputees. From an existing database, three transfemoral amputees who use prostheses were chosen. Their respective hips and femur were obtained from tomography, and so as their cartilages from their respective articular surfaces. Finite element models were created per patient and static bipedestation was analyzed. At the beginning of contact between cartilages, contact stresses were determined. The results showed that the stresses of the amputated side were higher than that of the non-amputated, in terms of average and peak contact stress. These were located in the anterior and superior zones, respectively.

Keywords: finite element method; transfemoral amputation; cartilage stress state.

Primer acercamiento a la mecánica de contacto en amputados transfemorales unilaterales

Resumen

Los esfuerzos en la cadera son de gran importancia debido a su relación con la salud articular. Modelos de elementos finitos pueden predecir el contacto entre cartílagos, sin embargo, modelos de contacto en amputados transfemorales unilaterales, no han sido encontrados aún en la literatura. Se quiere presentar un acercamiento inicial en la mecánica de contacto de la articulación coxofemoral de dichos pacientes. De una base de datos existente, se eligieron tres amputados transfemorales usuarios de prótesis; se obtuvieron sus respectivas caderas y fémures a partir de tomografía, y los cartílagos de las respectivas superficies articulares. Se crearon modelos por elementos finitos por paciente y se analizó la bipedestación estática. Se determinaron los esfuerzos al inicio del contacto articular, observando resultados mayores para el lado amputado, tanto para los esfuerzos promedio como para los esfuerzos máximos de contacto; y estos se encontraron en la zona anterior y superior respectivamente.

Palabras clave: método de elementos finitos; amputación transfemoral; estado de esfuerzos del cartílago.

1. Introduction

Amputation is a surgical procedure in which a limb is removed because of an illness or injury. A way of improving the quality of life of people that had undergone amputation is through the use of orthopedic prostheses, which replace their lost limb and provide them the possibility of recovering mobility and help in their reintegration into society [1,2]. Lower limb amputation is categorized into: toe, ray, transmetatarsal, mid-foot, ankle-level, below the knee, through the knee, above knee and hip disarticulation [3].

Depending on the amputation's location, different prosthesis is used.

In existing literature, studies of lower limb amputation are related to gait dynamics [4–7], socket design [8] and socket – stump interaction numerical models [9–11]. In addition to these, joints studies are associated with osteoarthritis (OA) development in the knee [12–14] and the hip [14,15], the influence of different sockets on the range of motion of the hip [16] and the effect of osteointegrated prosthesis on the hip joint moment [17].

Hip stresses are of great importance due to their relation

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to the joint's health. Cartilage health, in particular, is influenced by the magnitude and direction of the resultant hip forces, the size of the weight-bearing surface and the stress distribution across the said surface [18]. There have been cases wherein some anatomical conditions like femoroacetabular impingement [19,20] causing osteoarthritis (OA) because of abnormal contact stresses [21]. Furthermore, there are also disagreements regarding the normal magnitudes and distribution of contact stress on one's healthy hips [22]. For non-amputated subjects, finite element (FE) models have been developed as a way of understanding load distribution on the joint and predicting cartilage contact stresses on hips with and without pathological conditions [22–24]. Differences between healthy and dysplastic hips have been compared [25–27] and retroverted acetabula have been studied [28].

Computational methods can simulate hip joint mechanics and have thus been used to predict contact stresses [29–33]. Nonetheless, FE predictions of hip cartilage contact for unilateral transfemoral amputees have not been successfully found in literature. The objective of this study, therefore, is to develop a subject-specific numerical model to compare hip cartilage contact of unilateral transfemoral amputees between pathological and sound leg on standing position.

2. Materials and methods

As the first approach to this kind of models, a standing position model will be used, since it is not only the easiest load case but one that can predict if there is a stress difference on various sides. Three patients that had undergone unilateral transfemoral amputation were selected; their specific data is presented in Table 1. The patients were relatively active and did not have any additional physical, vascular, neurological or psychological condition that could affect the result of this study. The patients used a non-distal end support socket, a solid ankle cushioned heel (SACH) foot, and a mechanical monocentric knee prosthesis. In accordance to the ethics committee of Universidad Nacional de Colombia, proper and informed consent was given by each patient before any of the procedures took place

Table 1.
Patients' characteristics and applied force.

Patient	Age	Time since amputation (years)	Height (cm)	Weight (Kg)	Gender	Amputated limb	Applied force (N)
P1	50	2	163	60	Male	Right	300
P2	43	10	175	70	Male	Left	350
P3	51	8	171	70	Male	Left	350

Source: The authors.

2.1. Numerical models

2.1.1. Database and computed tomography

The database was composed by transfemoral amputees from Orthopraxis S.A. The parameters used for the scan were: SIEMENS/Emotion6 Scanner, 12mAs, 130 KV, 512x512 pxlmatrix, pixel size 0.758 mm, gantry tilt 0.00 and slice increment 1 mm; cross sections were obtained from the distal femur to about half hip. During the CT scan, the patients were in a laying supine position over the tomograph table and were not wearing their prosthetic socket or any additional element like socks or liners around their residual limbs.

2.1.2. Geometry reconstruction

From a previous study, the residual femur, the stump and the socket were reconstructed using a 3D and CT scanner. [11]. For each patient, cast molds were created by a technician, then scanned and reconstructed by NextEngine's Desktop 3D Scanner and ScanStudio™ software (Santa Monica, CA). From the tomographic information obtained, the non-amputated femur along with the hips were manually segmented from the image data using the VTK software. It is worth noting that the CT anatomical positions were maintained throughout the study to prevent the direction of the applied load from affecting the cartilage stresses.

For both legs, the femoral and acetabular cartilages were obtained by expanding their respective articular surfaces by 1 mm, Fig. 1. This expansion was well within the values reported in literature, which is specified to be from 0,93 to 2,3 mm [34-37]. The meshes were constructed using as reference the quantity of the elements of similar studies [21,25,26,38]. The layers of the cartilages were constructed with hexahedral elements using the Salome – Meca software. The cortical bone, the stump and the socket were discretized with tetrahedral elements. The trabecular bone was not included in the process since it yields little significance in terms of contact stresses [24]. The general representation of the geometries can be seen in Fig. 2.

2.1.3. Materials

The material properties are assigned in ABAQUS V6.12; the cortical bone, the socket and the stump were modeled as homogeneous, isotropic materials with an elastic modulus of $E = 15GPa$, $E = 1.5GPa$ and $E = 25KPa$ respectively; their Poisson's ratio are $\nu = 0.3$ for the cortical bone and the socket, and $\nu = 0.475$ for the soft tissue [11,39]. The cartilage was modeled as a homogeneous, isotropic, Neo-Hookean hyperelastic material. The Abaqus Neo-Hookean form was used in the process, with a shear modulus of $G = 13.6MPa$ and a bulk modulus of $K = 1359MPa$; the material constitutive parameters were calculated using eq (1) – (2) [40], $C_{10} = 6.8MPa$ and $D_1 = 1.4 \times 10^{-9} Pa$ [22].

$$\mu_0 = 2C_{10} \quad \mu_0, \text{initial shear modulus} \quad (1)$$

$$k_0 = \frac{2}{D_1} \quad k_0, \text{initial bulk modulus} \quad (2)$$

2.1.4. Contact properties, boundary conditions and loads

An explicit numerical model was developed using ABAQUS V6.12. The model was given general boundary conditions: no penetration and frictionless contact between the cartilages geometries [22] and a tie constraint between cartilage-bone and the bone-soft tissue to define the interfaces' interactions.

2.1.5. Amputated model

This model was developed in four various steps. Donning: where the constraints were applied to the hip (in the pubis and superior face) and in the neck of the femur, a part of the ischium was removed to prevent contact between the stump and the pelvis. Finally, the donning procedure of the socket was done by applying a displacement vector (white arrows) on the socket, Fig. 3a. Stabilization: a 5-second step was then applied to allow the attenuation of the dynamic effects caused by the location of the socket and the acquisition of the final position of the soft tissue.

In this phase, there are no existing stimuli or additional boundary conditions, Fig. 3b. These two steps were done as per Lacroix and Ramirez [41]. Load: within 10 seconds of the process, the load described in Table 1 (black arrow) was applied in a caudocranial direction over the socket at the interface of the femoral prosthesis' extension, representing half of the patient weight, Fig. 3c. The constraints remain the same for this step. Contact: the displacement vector (white arrows) on the socket and the boundary condition (constraints) of the femur were eliminated, which then allowed contact between cartilages; a new boundary restriction was applied over the socket (constraints) to remove its lateral movements, Fig. 3d.

2.1.6. Non-amputated models

These models were developed in two steps. Load: movement restrictions (constraints) were applied over the hip -pubis and superior faces. Afterwards, the loads (gray arrows) were applied in a caudocranial direction over the femoral condyles. This load is the same as described in Table 1, but were divided among the two condyles, Fig. 4. Stabilization: a 5-second step where no additional loads or boundary conditions were applied, allowing the stabilization of the model and the reduction of its internal energy.

2.1.7. Contact area and contact stresses

Cartilage contact stresses and contact area were evaluated on the acetabular cartilage. Contact area and peak contact stress were evaluated in the anteromedial (AM), anterolateral (AL), superomedial (SM), superolateral (SL), posteromedial (PM) and posterolateral (PL) regions of the acetabular cartilage [25], Fig. 5.

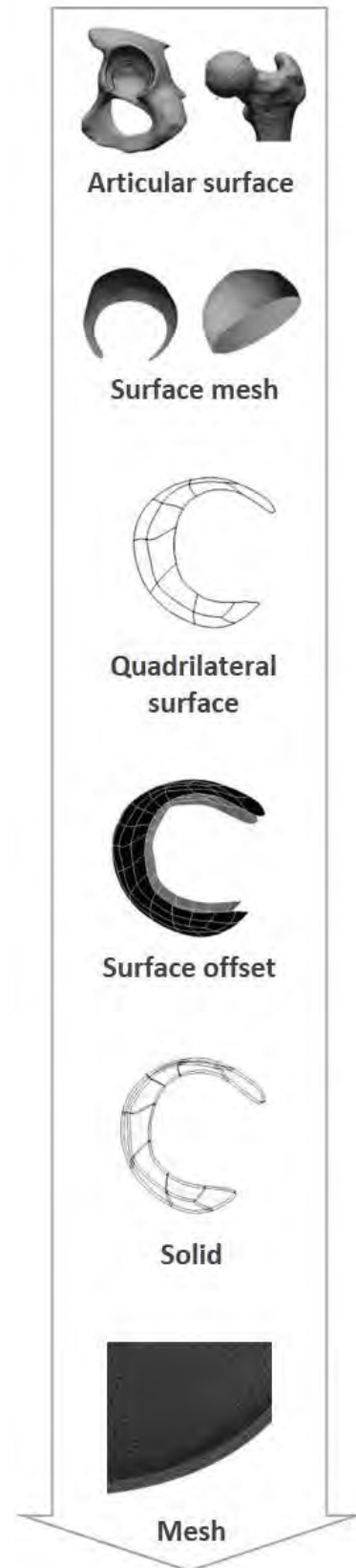


Figure 1. Cartilage reconstruction.
Source: The authors.

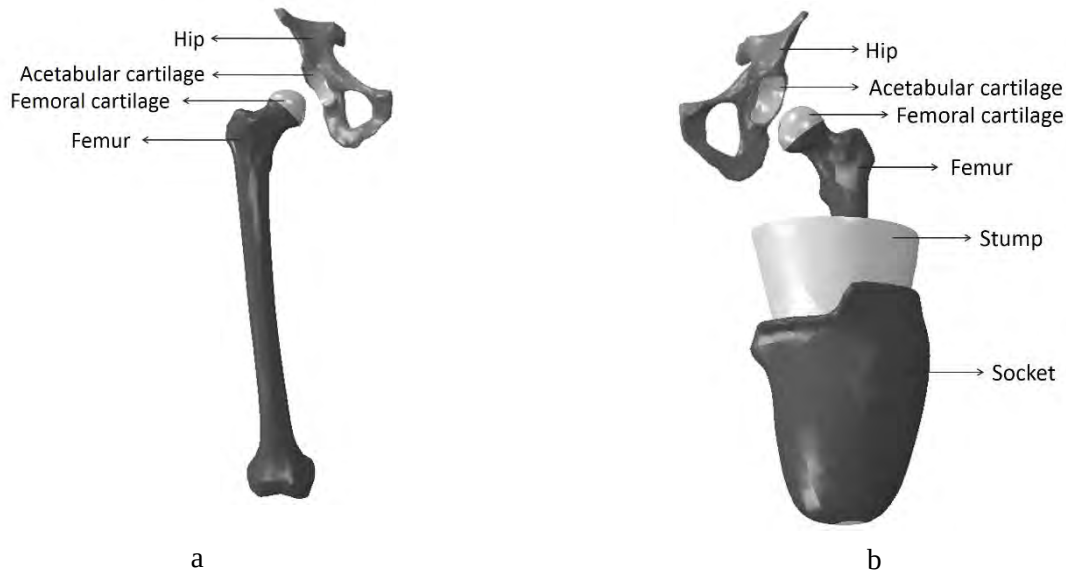


Figure 2. Subject-specific models. a. Non-amputated assembly, b. Amputated assembly.
Source: The authors.

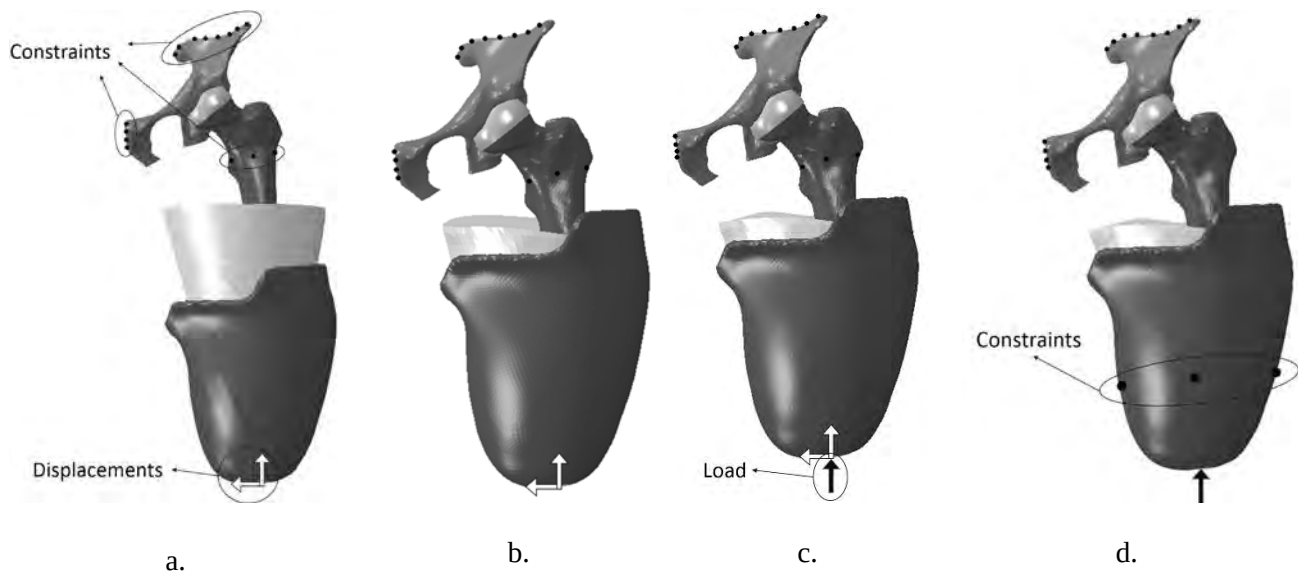


Figure 3. Amputated model boundary conditions. a. Donning, b. Stabilization, c. Load, d. Contact
Source: The authors.

Overall, the amputated side proved to have higher stresses than the non-amputated one; however, the contact stress patterns in patients and their amputated and non-amputated sides were not constant, as can be seen in Fig. 6. As for contact pressure (CPRESS), it shows that there are some few localized stress zones present while the remaining cartilage does not show these - a common behavior in this type of stress distributions [23,27,41–44] since there are areas that have high load and some that have none. Due to the model's

specific steps involved, the application time of the load varied between the amputated and the non-amputated sides. When the bone restriction was removed, the amputated models had almost immediate contact due to the stored energy, registering a time of 0.4 ± 0.1 seconds to have contact, while registering 3.8 ± 0.8 seconds contact for the non-amputated models, where the applied force was transferred progressively over the femur until contact happened.



Figure 4. Non-amputated model boundary conditions
Source: The authors.

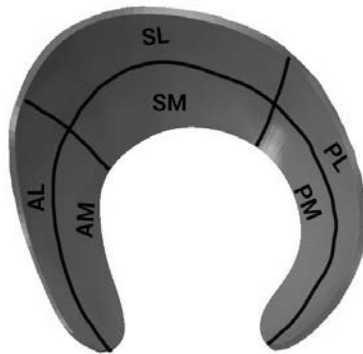


Figure 5. Anatomical regions on the acetabular cartilage.
Source: The authors

3. Results

The peak average and average stress were both determined in the first seconds of contact between cartilages; the average contact stresses were ~ 12 MPa for the amputated side and ~ 4 MPa for the non-amputated side. There were marked differences between the sides in both peak and average stresses in the PL and PM regions Fig. 7, as contact stresses at the posterior region were not present in the non-amputated side. The anterior region stresses were higher in the amputated side as compared to the non-amputated one, while the superior regions have also presented differences, although at a lower scale.

Stresses in the anterior region were the highest for the amputated side, while it was the superior region that registered the highest for the non-amputated one. However, both SL and SM were the regions with less variation in their stresses compared to the amputated one. Peak contact stress at the amputated side was higher than in the non-amputated side, Fig. 7, with the AL and the AM regions having the

highest contact stresses. In contrast, it was the SL and the SM that had the highest contact stress in the non-amputated side.

Fig. 8 shows the total contact area of the acetabular cartilages in the contact and the stabilization steps. The contact areas for the non-amputated side was smaller than in the amputated one, and it shows that cartilage contact is always maintained throughout the step, even though the values show small iterative behaviors. In contrast, the contact areas in the amputated models have spaces where there is no contact between the surfaces, and the curves show growth behavior and decrease in time.

The total acetabular cartilage surface area averaged 131.32 ± 40 mm² for the amputated side; with the contact area percentage of around 20% for P2 and P3, and 17% for P1. In comparison, the surface area for the non-amputated side was $134,11 \pm 17$ mm², with a contact area percentage of 15.4%, 14% and 11.3% for patients P1, P2 and P3 respectively.

4. Discussion

As expected, the main findings yielded some differences in the amputated and non-amputated side of each patient; however, changes to all the amputated and non-amputated sides were also observed in the contact mechanics (refer to Fig. 6.) These differences could be attributed to variations in bone and cartilage morphology [22,45], but other factors, such as stump and amputated femur lengths, load directions, anatomical position of the patient and the distance covered by the socket upon positioning it, can also affect stress distribution. Nonetheless, it is normal for small regions to have concentrated stress while the rest of the zones have none. [21,22,24,25,27,28,44,46,47].

Direct comparison with past studies in terms of numerical values for contact stress or contact area is inappropriate in this case since we have not successfully found hip numerical models for transfemoral amputees as of writing. Nevertheless, we have found that some of our results have similarities with other published works as will be shown below. Peak normal stress results for patients P2 and P3 (24 MPa and 20 MPa), were akin to the stress values reported in pathological hips by Henak et al. [25] and [28], so as for acetabular dysplasia (30 MPa) and retroverted acetabula (25 MPa). The stress results of the amputated and non-amputated models did not exceed that of the peak stresses reported in literature. However, it is important to note that in the case of amputated models P2 and P3, the stress values found when they were in standing position were approximately the same to that of Anderson et al's results [28] in heel strike when climbing stairs or when rising from a seated position, indicating that amputees may be experiencing higher stresses in doing simple activities. The standard deviation in the contact stresses is high for all the patients and all sides, which can be explained by the fact that each of the models is unique and thus possess nonreplicable features.

During simulation, the contact area on the amputated side was mostly in the AL region. It was also in the AM, SL, SM, PL and PM regions but in lower proportions. As for the non-amputated side, in comparison, contact was primarily at the SL and AL regions, with some at the SM zone. This

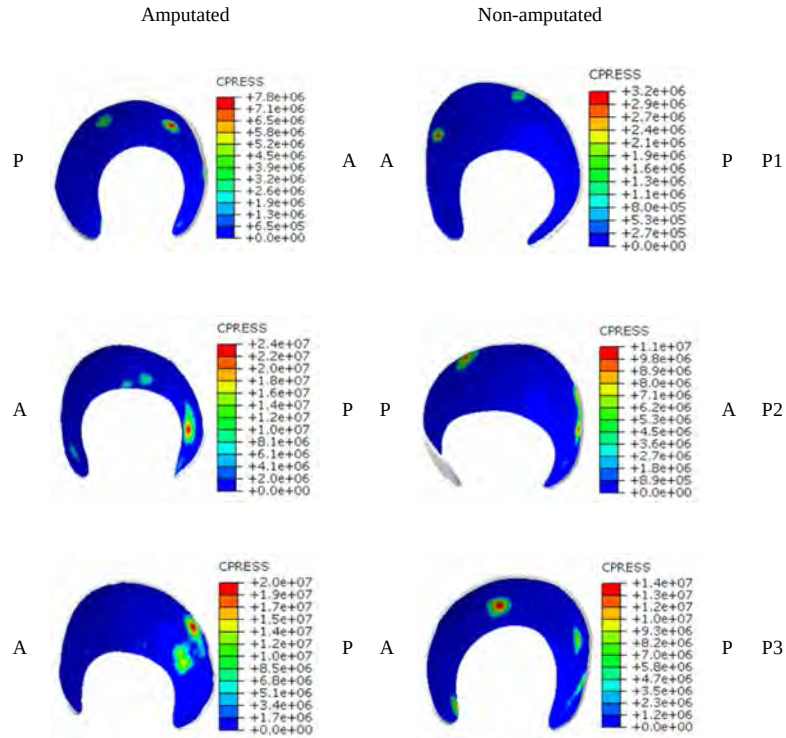


Figure 6. Contact pressure (CPRESS) on acetabular cartilages during Load step. A: anterior, P: posterior. The units are Pa, Source: The authors.

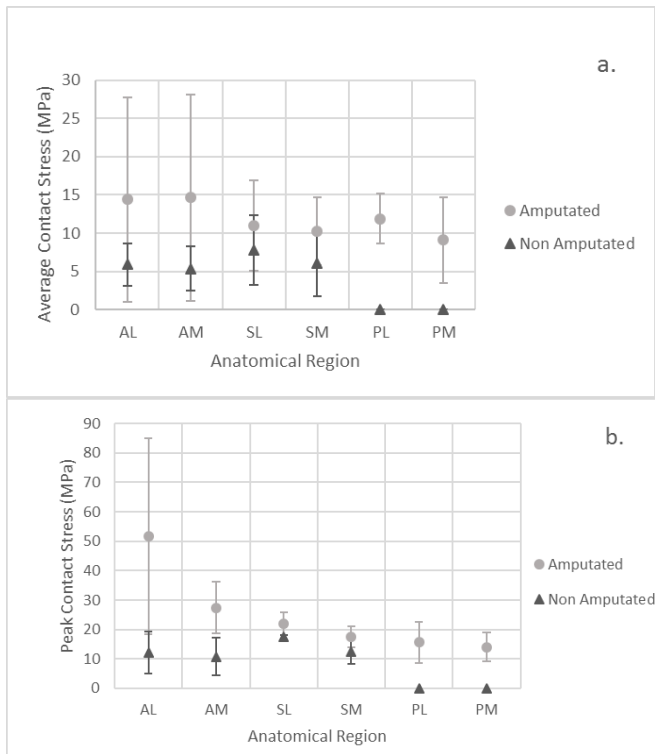


Figure 7. a. Average contact stresses, b. Peak contact stresses. Source: The authors.

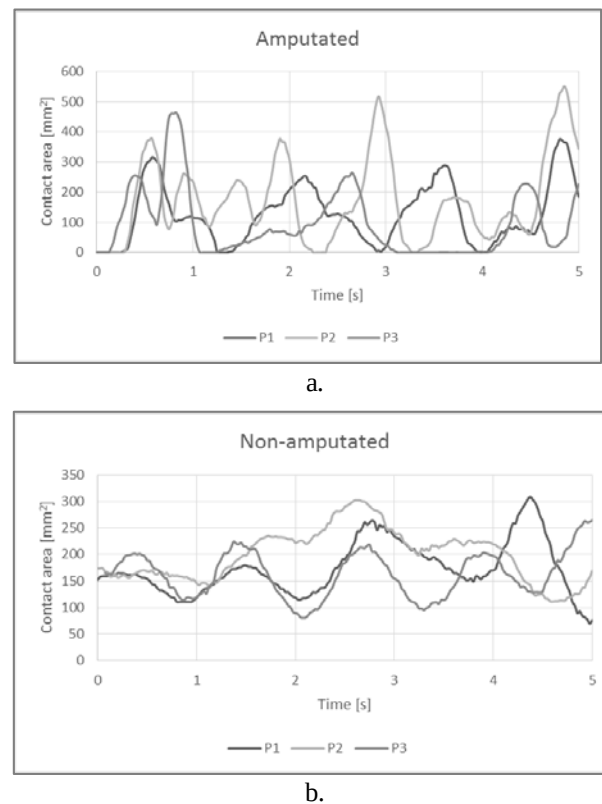


Figure 8. Contact area. a. Amputated, b. Non-amputated Source: The authors.

difference in both sides is likely caused by the residual energy stored in the stump during simulation, which then generates an iteration of contact. In general, the contact area on the amputated side was larger than in the non-amputated side, and there were no visible resemblances in the curves from between sides. Furthermore, similarities in contact area with previous studies were not found, except in the case of P1 where his amputated and non-amputated areas (374 mm² and 309 mm² respectively) were the closest to the average predicted value of a non-amputated hip (366.1 mm²) [24].

The models developed have several limitations that need to be discussed. First, the preliminary numerical models allowed us to observe that the internal energy stored in the residual soft tissue dislocated the hip in the standing position step. It was for this reason that the femur and socket constraints were applied to them. Moreover, because of the donning simulation, the soft tissue is represented as a unique volume, and the fibers that would have allowed control over the dislocation and that would have otherwise connected the hip and the femur, were not present. Adding muscle fiber or ligaments could have also helped prevent dislocation of the hip and made the numerical model more stable and fast, in terms of the model's completion. Second, the cartilage was assumed to be isotropic, nearly incompressible, and hyperelastic [21]. There are other cartilage models that might have allowed more accurate description of the tissue mechanical model – ie. the osmoporoviscoelastic models, [48], but poroelasticity models neglect the effects of inertia and are consequently not suitable for explicit analyses [49]. Finally, even though the models do not include the labrum, the FE model for the amputated side built in this study aims to progress toward a realistic interpretation of the transfemoral amputation. In contrast to other studies that evaluated donning of the socket without the articular joint [41,50], these models take into account the hip contact and the femoral and acetabular cartilages. There are other conditions that affect cartilage stresses –neck shaft angle, femoral anteversion angle and acetabular anteversion angle– as shown in [21], but for this specific case, our aim was to obtain a model where cartilage compression and socket donning are taking into consideration. The additional complexities explained above will be included in further studies.

4. Conclusions

Each individual is unique and thus each model has their respective differences and variations. The inclusion of the muscles that connect the hip and the femur and the understanding of their geometrical differences can change the model and make it more accurate. Our initial aim was satisfied, since the model was able to behave as expected. This study suggests that contact stress at the amputated side of the amputee are higher than that at the non-amputated side. And even though not all questions were answered by this study, there is no denying that it has generated additional issues that need resolutions through new analysis for a more complete understanding of these cases.

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Assessing the efficiency of science, technology and innovation using Data Envelopment Analysis (DEA): The case of Colombia

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Abstract

This paper provides insights into how to approach the assessment of scientific production efficiency using Data Envelopment Analysis (DEA). The methods employed in this paper take into account both the CCR and Assurance Region (AR) models, which are based on science, technology and innovation (STI) indicators. The sample focuses on the departments in Colombia as well as the Capital District (C.D.). The research concludes that both models calculate the efficiency of the units of analysis. Furthermore, according to the country's STI targets, AR is susceptible to hierarchies generated within the variables.

Keywords: assessment of scientific production; efficiency; science, technology and innovation indicators; Data Envelopment Analysis (DEA).

Evaluación de la eficiencia de ciencia, tecnología e innovación mediante Data Envelopment Analysis (DEA): Caso Colombia

Resumen

Se plantea una aproximación de medición de la eficiencia de la producción científica mediante el Data Envelopment Analysis (DEA): modelos CCR y Assurance Region (AR) con base en los indicadores de ciencia, tecnología e innovación (CTI) en los departamentos y en el Distrito Capital (D.C.) de Colombia. Se concluyó que ambos modelos calculan la eficiencia de las unidades de análisis, siendo AR susceptible a jerarquizaciones generadas en las variables de acuerdo a los objetivos país en temas de CTI.

Palabras clave: medición de producción científica; eficiencia; indicadores de ciencia, tecnología e innovación; Análisis Envoltente de Datos (DEA).

1. Introduction

Science and innovation indicators demonstrate the potential of the technical scientific information that is generated by a country [1].

Scientific journals are the fundamental channel of formal communication within the scientific community [2]. The number of patents applied for or granted and the number of papers published in journals that have a high impact factor are indicators that are used to measure the quality of research [3].

On the global scale, the Organization for Economic Co-operation and Development OECD has published handbooks to assess activities relating to science, technology and innovation, such as the Oslo Manual (1997), the Canberra Manual (1995), the Manual of Patents (1994), the Technology Balance of Payments (TBP) (1990) and the Manual of Frascati (1963) [4].

The Administrative Department of Science, Technology and Innovation (Colciencias) in Colombia frequently monitors research groups. Colciencias has implemented a pattern to classify research groups using the categories A1,

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A, B, C, D and recognized (Rec), which follows the research group indicator. The coefficient is assigned according to the categorization of four scientific elements: development of innovative knowledge, technological development, social appropriation of the knowledge and training of human resources. Furthermore, the pattern classifies researchers into three categories (Senior, Associated and Junior) according to their academic degree and their academic production [5].

The report entitled 'State of Science in Colombia' was written in 2015 and detailed the production of research in the different administrative divisions (departments) according to the four product categories. The indicators take into account investments in science, the number of scholarships granted, research centers and research groups, recognized researchers and registered products [5].

Some scholars have encouraged researchers to measure scientific production, which includes: measuring university research [6], the influence of the size of the institution, and the number of researchers producing scientific research in the centers [7]; scientific production in biological and health sciences in twenty Brazilian universities [8]; measuring scientific production in the field of the psychology [9]; and the empirical study of scientific measurement [10].

The above areas of research evaluate the number of products developed by the units of analysis. Other scholars make measurements in terms of efficiency; however, this involves two serious challenges: First, the research needs to develop standard criteria to compare the data collected from reality. Second, some cases analyzed are designed with complex organizational structures with multiple inputs and outputs for endowments and products, which do not assess efficiency with suitable precision. Therefore, the researcher should allocate weighted values according to trade-offs and factor endowments [11]. The mathematical application *Data Envelopment Analysis* (DEA) is such an alternative solution.

Some research that has used the DEA model has measured efficiency in the following areas: research projects in two clinical centers [12], national innovation systems [13], innovation in each German region [14], international comparisons of efficiency among the national innovation systems [15], analysis of scientific and technological activity [16], technology and knowledge transfer in Spanish public research centers [17], research groups in Andalucía [1], innovation regional systems in 31 Chinese provinces [18], classification of research group in Colombia [19], R&D activities according to the number of patents submitted in the European Union [20] and research activity at Valladolid University [21].

Based on data from Colciencias, this paper details the advantages and features of DEA application in order to measure scientific activity in Colombia.

2. Theoretical approach

2.1. Science, Technology and Innovation.

Science, Technology and Innovation (STI) are core elements that should be used to develop sustainable knowledge in societies. STI has the potential, nationally, to be a significant engine for social and economic development.

National and regional policies promote both investments and human resources training. These activities strengthen the abilities to link STI to sustainable growth [22].

Colciencias annually up-dates the assessment framework for scientific production in Colombia. The adjustments made are based on global standards that classify the research abilities and technological development of recognized research groups and researchers in Colombia. Despite this, research activity in Colombia remains far removed from developed countries. Investments into activities relating to science, technology and innovation (ASTI) represent only 0.5% of GDP in Colombia; investments into Research and Development (R&D) represents 0.2% [5].

2.2. Data Envelopment Analysis (DEA)

DEA is a technique based on linear programming the purpose of which is to help maximizing the efficiency of each decision making unit (DMU). Every DMU could be a functional unit, a process or a group that demands inputs and supply outputs [23]. There are two ways of measuring DMU efficiency [24]:

- The input-oriented method: the quantity of resources is minimized in order to get the best level of production.
- The output-oriented method: the quantity of manufactured products is maximized by a fixed level of inputs.

DEA offers a method to find a set of proportions based on the assumption that all observed data is homogeneous. The aim is to maximize the function of relative efficiency of the DMU; however, this is subject to the radius of the DMU not being bigger than the unit. The border of efficiency can be variable with the BCC model or constant with the CCR model. Specifically, this research uses the CCR output-oriented model, which is represented by the following formulation (1):

$$\begin{aligned} \text{Min}_{u,v} \text{Zo} &= vX_o \\ \text{s.a:} \\ uy_o &= 1 \\ uY - vX &\leq 0 \\ u \geq 0; v &\geq 0 \end{aligned} \quad (1)$$

CCR-O is taken as a baseline for the application of the *Assurance Region* (AR) model, which establishes the limits at the top and the bottom for the weighted values. This allocation depends on whether the restrictions only affect the weights input and / or output [25].

3. Research methods

The application of the model was carried out in four phases: The first was the categorization of the information that is consolidated in the 'State of Science in Colombia' document using input and output variables; this information was subsequently selected depending on its relationship and direct influence on the states' research efficiency. In the second phase, the constant scale generated by the CCR model was selected, which is oriented to the outputs as the products are susceptible to improvement. In the third stage, the CCR-O

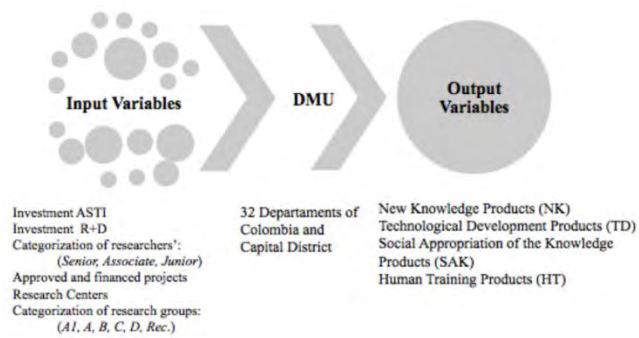


Figure 1. Selected variables
Source: The authors.

is applied and is taken as the basis for the Assurance Region model in order to adjust the efficiency measurement by means of weight restrictions assigned to products. This is more in line with the Colciencias' evaluation of each one of the types of products. The final phase refers to the interpretation of the efficiency levels determined by the two models applied.

3.1. Selection of variables

The research calculated the global results of 32 departments in Colombia. The Capital District (Bogota) was also observed due to its significant level of research production: the result was that a total of 33 DMU were obtained. The "State of Science in Colombia" exhibits information that shows the dynamics and general lines of Colombia's science and technology (S&T), which are the variables used to apply the DEA model to each of the items in the report. They are classified as being either input and output variables and have a set of values for each unit of analysis. This operation (shown in Fig. 1) assumes that both monetary investments and human capital of every DMU are the inputs used develop research products.

Fig. 1 shows 15 input variables, which include categories and subcategories, 33 DMU and four output variables. The number of variables was reduced because of the operationalization of the DEA model. Otherwise, the number of efficient DMUs would have been high, which would have allowed them a higher number of possible combinations and been a grade closer to the efficiency border. Nevertheless, the reduction in variables does not generate substantial loss of information for the application.

First, three variables related to 'categorization of researchers' were united into one variable. The same process was then applied for the six 'categorization of research groups' variables, and it was taken into account that these variables have a hierarchical order that is represented in particular categories relating to effort and research relevancy. The following paragraph explains the criteria used to unify the variables.

The weighting scale with the values proposed in Colciencias' last scheme of measurement was applied to assess research and research groups. This scale is coherent with the relevancy and the level of contributions to the

Table 1.

Weighting value for category of research groups

Weighting value for category of research groups in Colombia						
Groups	A1	A	B	C	D	Rec.
Category						
Weighting value	10	8	6	4	2	1

Source: The authors.

science described within the classification (c.p Table 1). Therefore, the value of these variables is a weighted sum. The two variables presented a co-relation of 0.994. Overall, 'research groups' was the representative variable, taking into account that researchers' production contributes to the classification of the research groups.

Moreover, Colciencias also observes the investment in ASTI and R&D as independent categories in order to differentiate them. However, this research grouped them into one variable as they are complementary [26].

Scholarships awarded for Master's and PhD programs were not included in the project as input variables because the products of this investment will become reflected in the selected output variables in the medium-term after the students have finished their education. The following are used as the input variables:

- Research centers and technological development that are recognized and strengthened by Colciencias, according to information from the period 2009-2013.
- Research groups that were recognized and classified by their particular field of knowledge and for their scientific and technological production (results based on call for applications 693 of 2014).
- Approved STI projects financed by Colciencias, the values of which were calculated at constant 2013 prices and correspond to the period 2010 – 2013.
- Investment in science, technology and innovation (ASTI) and research and development (R&D) activities as a percentage of the GDP. This investment relates to the year 2013.

Four types of products were taken as output variables: new knowledge (NK), technological development (TD), social appropriation of the knowledge (SAK) and human training (HT). This information allows researchers to identify the target of each DMU's effort.

3.2. Application of the model

This research used two DEA models as a reference. The first is the Assurance Region (AR), which maintains a hierarchy within the output variables. In this research, this refers to the different types of products developed by the research in Colombia; the second is the CCR-O model. Unlike the previous model, CCR-O does not provide any type of restriction when allocating weighted values for both input variables and output variables.

The AR model uses the CCR-O model as a baseline, which results in a constant scale. Specifically, in the Colombian case, every type of product counts on a different significance level, which depends on the research groups in Colciencias' scheme of assessment. The calculated weighted values can be found in Table 2.

Table 2.
Weighted values for the type of research products

Weighted values for the type of research products				
Type of product	New Knowledge (NK)	Technological Development (TD)	Social Appropriation of the Knowledge (SAK)	Human Training (HT)
Weighting value	43.47	38.04	2.17	16.32

Source: The authors.

Table 3.
Limits of the restrictions between product relations

Inferior limit	Relation	Superior limit
8.585	NK/SAK	46.742
0.999	TD/HT	5.439
0.49	NK/TD	2.666
1.141	NK/HT	6.215
7.513	TD/SAK	40.903
3.223	HT/SAK	17.548
0.021	SAK/NK	0.116
0.184	HT/TD	1.001
0.375	TD/SAK	2.042
0.161	HT/NK	0.876
0.0244	SAK/TD	0.1331
0.057	SAK/HT	0.31

Source: The authors.

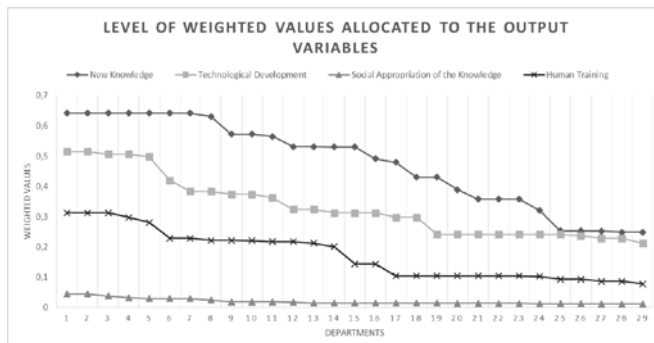


Figure 2. Level of weighted values allocated to the output variables
Source: The authors.

According to the weighted values (Table 2), each variable has a restriction when qualifying the efficiency of the DMUs, which is related to the proportion of weight assigned by DEA. Both the best and the worst stages were calculated for each of the possible relations between the products in order to establish the limits of the restrictions. Those limits can be found at the top and the bottom of data. Table 3 includes the limits of restrictions between product relations.

The *Assurance Region* model allows us to identify the weighting values assigned to each of the output variables for the DMUs. Considering their restrictions, they maintain the levels of relevance that are assigned to the types of research products by Colciencias, as shown in Fig. 2.

The CCR-O model does not take into account any kind of restriction. CCR-O freely allocates the most convenient weighted values to each DMU, according to the levels of the input variables and output variables.

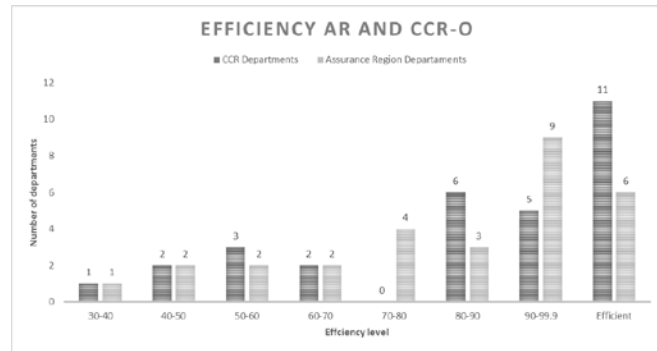


Figure 3. Efficiency of the AR model and CCR-O model
Source: The authors.

4. Main findings

The application of the CCR-O model and AR model identified the DMU, which appears to be both efficient and inefficient depending on the levels that are described for the input variables and output variables. Furthermore, the research indicates the group of reference for the inefficient units. In addition, the results allow us to find the variables which need to be improved in order to be efficient. Finally, the research looks at the weighting assigned to the variables.

Four DMU were eliminated from 33 departments when the models were applied (Guainía, Putumayo, Vaupés and Vichada) as they offered values equal to zero in all their output variables. They were, therefore, disqualified from the analysis. Both models were output-oriented and were solved by the Software DEA Solver because the aim of this research is to determine the efficiency of the departments in Colombia and the Capital District in terms of their scientific production. The frequency of efficiencies for the DMUs were obtained and can be seen in Fig. 3.

Fig. 3 offers the DMUs according to the different ranges of efficiency levels for each model. The CCR-O model identified a higher quantity of technically efficient DMUs than the AR model. This difference is explained due to the AR model being more rigorous with restrictions that limiting the weighting values allocation. Neither the CCR- O nor the AR models described were Pareto-efficient DMUs because at least one of their variables was assigned with a zero weighting value.

The CCR-O model developed a border of constant efficiency that is shaped by the DMUs, which appear to be efficient. This takes into account that the aim of the projections in the model is to lead the inefficient units to the border. Based on this, efficient DMUs are converted into references that do not appear in the same situation. Fig. 4 shows how many times a DMU was referenced in each of the models, and a ranking is generated within the efficient DMUs since a higher frequency as a reference, implies a better performance of that unit compared to other efficient units [1].

Overall, Boyacá stood out as a global leader as it was efficient in both models as it had the biggest indicator such as modality of inefficient units. Amazonas and Atlántico came second and third in the number of DMUs. Cesar, Córdoba, Capital District, Caldas and Magdalena, which has a 'zero' frequency in the AR model, stopped being efficient after they were included in the restrictions of hierarchical structuring of the level of importance that was awarded to the research products.

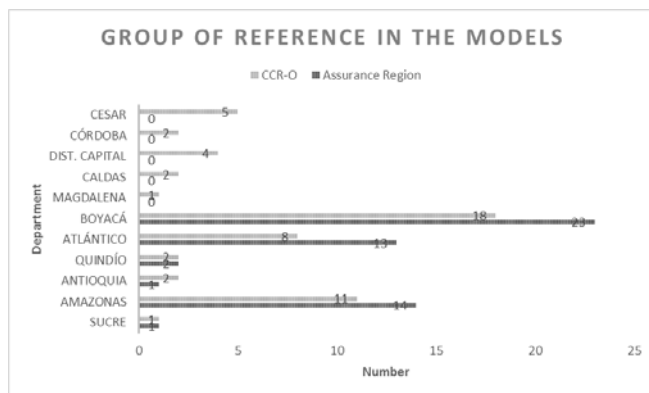


Figure 4. Group of reference in the models
Source: The authors.

DEA shapes the groups of reference in order to propose improvements to the inefficient DMUs, according to the levels presented by them. The goal is to achieve efficiency through identifying the variables and quantities which must be modified.

The main improvement is proposed for output variables because the CCR model and AR model are output-oriented. Despite this, some DMUs need the input variables to be further modified in order to become efficient. In this case, the models coincided with the type of variables that need to be changed in either a major or less manner so that the analysis units become efficient. The following variables should be adjusted with a descending relevance: products of technological development, social appropriation, human training and products of new knowledge.

Despite the models being output-oriented, both proposed modifications for some of the input variables. Investment in ASTI and research centers developed major amounts of change. This indicates that some departments are not developing enough products that justify the resources used as there are DMUs which achieved major production with less resources for those variables.

5. Discussion and conclusions

There is no evidence in Latin-American scientific reports regarding assessing the efficiency of the scientific activity on a regional level. 59% of research used CCR and 40% of research used BCC from all the projects that used DEA. The remaining 1% of projects used Super Efficiency, Crossed Efficiency and a proper guideline. None of the cases used the Assurance Region model. Therefore, there were no restrictions considered with incidence for the share of the weighting values assigned to the variables by DEA.

More than 95 % of the research analyzed used the human and financial resources as input variables. Moreover, 70 % of the research used patents and publications (papers and books) as output variables. The share of efficiency for the units of analysis ranged between 20 % and 66 %. For this exercise with CCR, the proportion of efficient DMU was 38 %, and when the AR was adjusted, the proportion was lowered to 21 %. This share makes more rigorous estimation possible because it includes restrictions that refer to levels of

importance regarding the output variables. In the both cases, there were no Pareto-efficient DMUs as, at least in one of the variables, a weighting value of zero was allocated. Therefore, they were technically efficient.

Broadly speaking, the both the CCR model and the AR model allow researchers to undertake a measurement of STI approach. The AR model is suitable for hierarchical structures developed in the variables by the particular entity that manages the STI in each of the countries.

Researchers are concerned about efficiently measuring scientific up-dates. The main patterns used to be able to evaluate scientific activity are the high human resource skills and the relation they have with proper, public and private funds. These patterns allow research centers to generate products such as new knowledge, technological development, social appropriation and human training.

Furthermore, there is an opportunity to carry out a comparative study in other countries using the AR model, which allows researchers to determine hierarchical structures within the output variables, according to the CTI targets in the country. A multi-centric model can also be applied to compare the DMU case study.

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Continuing evolution of model free. Evolution of trade zones in the world with an emphasis in the Latin American

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Abstract

Trade zones (TZ) has been an important pole as a driver of contemporary world economic development. The article presents the different typologies of the zones, and describes their evolution in the world, their economic and social impact and the distinctive factors of their development in the Latin America region. The results show that the region has one of the highest development dynamics of the TZ in terms of both number and employment, however, the impact is low in the development of value in both the human and innovation aspects. It is necessary to strengthen the TZ model that governments encourage the development of downstream productive processes and associated support processes, both in increasing value and improving the quality of life of human capital, as well as in the aspect of legal mechanisms in order to improve the international trade and thus to maintain the dynamics of development.

Keywords: Free Zone; supply chain; globalization; economic development.

Evolución del modelo de zonas francas permanentes en el mundo: Con un énfasis en el caso Latinoamericano

Resumen

Las zonas francas han sido un importante polo dinamizador del desarrollo económico mundial contemporáneo. El artículo presenta las diferentes tipologías de las zonas, y describe su evolución en el mundo, su impacto económico y social y los factores distintivos de su desarrollo en la región Latinoamérica. Los resultados muestran que la región tiene una de las más altas dinámica de desarrollo de las ZFP tanto en número como en empleo, no obstante, el impacto es bajo en el desarrollo de valor tanto en el aspecto humano como en la innovación. Es necesario para potenciar el modelo de ZFP que los gobiernos incentiven el desarrollo de procesos productivos ascendentes y de procesos de soporte asociados, tanto en el aumento de valor y mejora de la calidad de vida del capital humano, como en los mecanismos legales en pro del comercio internacional para mantener la dinámica de desarrollo.

Palabras clave: Zona Franca; cadena de valor; globalización; desarrollo económico.

1. Introducción

La zona franca (ZF) representa uno de los mecanismos utilizados por los Estados para desarrollar la inversión Extranjera (IED). Las ZFs han sido un mecanismo generador de exportaciones, fue su misión sustantiva en los años noventa, y de empleo, especialmente desde la primera década del siglo XXI. Los primeros indicios de la aparición de las ZFs especiales (ZFEs) se remontan al siglo XIII en España,

cuando el Rey Alfonso X de Castilla, “El Sabio” otorgó concesiones especiales al puerto de Cádiz, una vez fue liberado de los musulmanes, para el trasbordo de mercancía como parte de una estrategia económica que incluía la reforma de la moneda y la promoción de numerosas ferias de comercio. Así mismo, en 1242 las ciudades de Hamburgo y Bremen desarrollan una alianza comercial denominada la Liga Hanseática que buscaba desarrollar intercambios comerciales con Rusia y Europa del Norte, más adelante en

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el siglo XVI, los puertos de Trieste, Génova y Marsella se convierten en los dinamizadores de las franquicias aduaneras del comercio europeo, iguales derroteros tuvieron en el siglo XVIII, Adén, Gibraltar y Singapur [1]. La evolución principal de las ZFs se da en el siglo XX después de la segunda guerra mundial, cuando se dio sistemática y paulatinamente en todos los continentes siendo actualmente sus principales exponentes Asia y Latinoamérica.

Esta figura evoluciona gracias al surgimiento de las nuevas condiciones y políticas establecidas para el comercio internacional como son los tratados de libre comercio (TLC), los acuerdos comerciales transregionales, e intercontinentales y la liberación y minimización de aranceles, medidas que han propiciado que las empresas se integren a los países a través de las nuevas dinámicas industriales. La aplicación de estos desarrollos implica desafíos en términos de productividad que incluyen avances logísticos en infraestructura, transporte eficiente, almacenaje y despachos inteligentes, tanto en los esquemas de recorrido e integración de insumos y fabricación como en la confiabilidad y velocidad de entrega de los insumos, bienes y servicios conexos [2,3]. Todo ello está soportado ahora por el creciente y vertiginoso desarrollo y posibilidades de acceso a nuevas alternativas de mercados y tecnología de comunicaciones que facilitan el flujo de materiales e información en contextos globales. [4] explica que en el momento en que las organizaciones consideraron el factor tecnológico como determinante de las ventajas comparativas, el comercio paso a fundamentarse en las ventajas absolutas, basado en la instauración de las diferencias tecnológicas internacionales que ponen en entredicho el concepto de las ventajas comparativas [5].

[6,7] presentan algunos de los primeros análisis de instancias como las ZFs, los cuales cobran una inusitada relevancia debido a que la figura económica facilita la operación de la Cadena de Abastecimiento (CA) para que sea más efectiva, en sintonía con las exigencias de la operación global [5,8]. Otros elementos se han incorporado en la conformación del actual tejido constitutivo del comercio internacional, como son la multiculturalidad empresarial endógena en las empresas, cambios alineados al establecimiento de gobiernos corporativos, la necesidad de sincronizar los procedimientos productivos en diversas regiones del mundo e integrarlo en modelos eficientes en términos de costo, conceptos que justifica estrategias como la de ZF. Desde la década pasada y en lo corrido de los primeros lustros del siglo XXI, la relación entre el desarrollo de las estructuras organizacionales que incorporan procedimientos productivos descentralizados van acompañadas de segmentación de actividades y protocolos generalizados de producción junto a la asimilación de conocimientos, adquisición de desarrollo e innovación tecnológica, especialización y empoderamiento del colaborador de la organización. Esto en conjunto permite abaratar sustancialmente los costos, y aumentar las coberturas de mercado y apertura de nuevas oportunidades de mercado en economías emergentes o en vías de desarrollo.

El trabajo presenta el desarrollo de las ZFPs, los componentes fundamentales del proceso y desarrollo de los esquemas de comercialización internacional actual. Se

realiza una revisión de la literatura, la evolución de la figura de las ZFs, su impacto económico y social y los factores que caracterizan su desarrollo en Latinoamérica. La información obtenida permitió determinar el contexto de desarrollo de las ZFP. Al respecto, la región muestra una de las más altas dinámicas de desarrollo de las ZFP tanto en número como en su impacto en el empleo, no obstante, el impacto es bajo en lo que atañe a diversificación de los tipos en especial hacia aquellos de más valor, tanto en el aspecto humano como en el de innovación. Es necesario para potenciar el modelo de ZFP incentivar por parte de los gobiernos el desarrollo de un proceso productivo ascendente y de procesos de soporte asociados, tanto en el aumento de valor del capital humano y mejora de su calidad de vida como en el aspecto de mecanismos legales en pro del comercio internacional, todo ello para mantener la dinámica de desarrollo.

2. Desarrollo

Las ZF son un instrumento esencial en la estrategia de industrialización con orientación a la exportación centrada en la IED. Los países se encuentran “compitiendo entre sí para ofrecer...incentivos y...privilegios lo más generosos posibles para atraer a los inversores y a los empresarios” [9]. Las ZFs permiten diversificar el desarrollo industrial, mejorar la situación fiscal, gracias al ingreso de nuevos recursos por pago de impuestos, regalías, transferencias tecnológicas; e impactar positivamente en el mejoramiento social de la población, al generar nuevos puestos de trabajo [10]. También es destacable la manera como las ZFs han sido base para el crecimiento moderno del comercio, ya que contribuye a diversificar la exportación de productos desde diversos y distintos lugares del mundo, coadyuvando a la integración de procesos productivos, convirtiéndose en vectores del desarrollo de empresas manufactureras descentralizadas, para estimular procesos productivos más rentables y mejorar las capacidades productivas, sociales y económicas de las naciones que apuestan fuertemente a este modelo de negocio [2]. El avance de la ZF se marca en su proliferación, vinculando cada vez a más países, y diversificación, incorporando diversos sectores productivos y de servicios [11].

2.1. Tipologías y funcionalidades de las ZF

Un estudio de la OIT [2] señala que, hoy en día, países del escenario Latinoamericano como Colombia o Uruguay y R. Dominicana, cuentan con ZFs diseñadas específicamente para empresas de sector, bajo la figura de Zona Franca Permanente Especial (ZFPE), que agrupan a empresas dedicadas a un solo sector de la economía como p.e. los textiles. Por su parte, la Zona Franca Permanente (ZFP) se define como el área donde se establecen diversas empresas que se desempeñan en diversos sectores de la economía sin distingo de ser industriales, comerciales o de servicios. A este conglomerado lo gerencia un operador, el cual tiene la licencia de concesión para administrar la zona [12]. Esta connotación ha sido tomada como referente para mostrar la evolución de las ZFs en el contexto histórico y económico moderno en el mundo [11]. La ZFP, la cual en esencia es

similar a las ZFs comunes, disfruta de las mismas exenciones de impuestos y demás ventajas del modelo de negocio, asumiendo además la función productiva, que consiste en desarrollar adicionalmente procesos de fabricación, transformación, envasado o re envasado y empaquetado de materiales destinados bien sea para la exportación, sin necesidad de realizar trámite de nacionalización ni pago de impuestos locales, o bien para abastecer un mercado local con preferencias arancelarias.

[13] Definen objetivos según las diferentes figuras de las ZFs, así como sus características, contemplando los diversos usos que los gobiernos le dan a esta figura económica, bien sean para comercio, industria, aduana, puertos libres, etc. La clasificación contempla las siguientes tipologías de ZF.

- **Customs Bonded Factories (CBF)**, son organizaciones industriales que orientan su productividad al ejercicio exportador, se ubican en zonas determinadas por el gobierno, pero se pueden ubicar en cualquier lugar del territorio, para el caso de nuestro estudio las denominaremos (ZFP) y gozan de los privilegios y exenciones provistas por el gobierno que rige la ZF.
- **Customs Bonded Warehouse (CBW)**, ésta es la más clásica de las ZFs, *Free Trade Zone (FTZ)*, asociada a zonas no mayores de 50 hectáreas, dedicadas al almacenamiento temporal, trasbordo, aduanas y logística de mercaderías que están dirigidas a la exportación.
- **Export processing zones (EPZ)**, se configuran como áreas aisladas, que se determinan como conglomerados industriales y que no tienen ninguna injerencia por parte del país patrocinador, en lo referente a impuestos y trabas arancelarias y aduaneras, estas serán denominadas (ZFPE), Zonas Francas Permanentes Especiales, en ellas se pueden realizar todo tipo de actividades comerciales o industriales y se ubican en lugares donde el proceso logístico se les facilite como aeropuertos y puertos.
- **Freeport**, es cuando un territorio de un país, como un puerto o una ciudad, se convierten en una ZFPE, se caracterizan por qué se puede desarrollar cualquier tipo de actividad comercial, sin límites ni montos económicos, se pueden transar y vender productos en los mercados locales e igualmente esta libre de impuestos, ejemplos de este modelo son Colon en Panamá o Hong Kong en China.
- **Special Economic Zones**, estas ZFs, son especiales en el sentido que son zonas geográficas delimitadas en donde los controles fiscales y aduaneros del país otorgante no tienen ninguna injerencia, la ZF cuenta con un régimen normativo diferente al del país, este marco como se le denomina se extiende a los aspectos de orden comercial, legal y lo regula un consejo de gobierno.

El principal incentivo para la implementación de estos centros productivos en un contexto de CA son las diferencias de calidades y costos, especialmente laborales, que se dan en países con economía emergente o en desarrollo a favor de las empresas [14]. Finalmente, las ZF permiten generar un enfoque de manejo que converge en dos tipos de modelos: 1. por un lado están los Administradores u Operadores Económicos Autorizados, los cuales pueden ser alianzas público-privadas o privadas, quienes se encargan del desarrollo de las zonas según su clasificación y 2. Están los

Tabla 1.
Experiencias de diversificación de ZF.

Tipo de Zona	Objetivo de Desarrollo	Actividades	Mercados
Con su base en los aeropuertos	Carga aérea y transbordo	Almacenaje, transbordo	Re-exportación y doméstico
Parques de Ciencia y Tecnología	Promover la alta tecnología y las industrias basadas en ciencia	Actividades de alta tecnología	Doméstico y exportación
Software e Internet	Desarrollo de software y servicios de tecnología de la información	Software y otros servicios de tecnología de la información	Exportación
Villas de Carga o Parques Logísticos	Apoyo logístico	Almacenaje, transbordo	Re-exportación
Zonas especializadas	Promover industrias específicas	p.e. Petroquímicas y otras industrias pesadas	Doméstico y exportación

Fuente: Elaboración Propia.

Tabla 2.
Experiencia de las ZF de Exportación en Latinoamérica en 2015.

Tipo de ZF	Concepto	Países de Latinoamérica
ZF PARA EXPORTACIÓN		
Diversificación Industrial	Permiten desarrollar procesos productivos integrados a CAs, exento de impuestos y se especializan en ciertos segmentos de la industria, como textiles y tecnología.	Costa Rica, República Dominicana
Maquilas o dependientes de transferencia tecnológica corporativa.	Transmisión de conocimientos y tecnología y desarrollo tercerizado de costos	El Salvador, Honduras, Guatemala, Nicaragua y México
Servicios Logísticos	Distribución de bienes y servicios	Panamá, Chile, Argentina y Uruguay.
ZONAS DE IMPORTACIÓN Y SUSTITUCIÓN		
Zonas Libres de Importación	Importación de productos para sustitución de mercado Local	Brasil
ZONAS MIXTAS		
Zonas de desarrollo permanente	Zonas especializadas en desarrollo de diversos segmentos de la industria	Colombia Uruguay y Rep Dominicana
Zonas especializadas para únicas compañías	Zonas destinadas a empresas o segmentos únicos de la industria	
Zonas de tránsito y almacenaje ocasional	Zonas de bodegaje y almacenamiento o de producción únicamente para exportación	

Fuente: Elaboración propia.

usuarios quienes son los que se instalan en las ZF para realizar sus actividades comerciales. La Tabla 1 clasifica las Zonas Libres de Exportación en el contexto de diversificación presentes en Ibero-América.

A continuación se presenta la Tabla 2 con la experiencia latinoamericana en donde se evidencia la carencia de Parques de Ciencia y Tecnología asociados a la figura de ZF:

2.2. Impacto económico de las ZFs

Latinoamérica ofrece una serie de beneficios y ventajas competitivas que la hacen atractiva para la inversión. Según [15], la región posee más de 400 ZFPs de las 800 establecidas

en el continente y un mercado cercano a los 570 millones de habitantes. En la región se han establecido más de 50 TLC, entre ellos con naciones y bloques altamente industrializados como EEUU, China, Japón, Corea y la UE. En la región se generan a través de la figura más 900 mil empleos y cerca de 8000 compañías tienen asiento en las ZFs. El 65% de las exportaciones de la región, se derivan de las ZFPs y ZFPEs, estas a su vez pueden generar 8 veces más rápido empleo que las empresas normales del mercado, gozan de beneficios tributarios establecidos por cada país de la región, más del 45% del empleo de las ZFs es formal y cerca del 70% de ellas contratan servicios con empresas del país donde está asentada la ZF y sus CAs.

La implementación de esta estrategia se ha traducido en buena parte en procesos de maquila. La experiencia mexicana, p.e., ha mostrado la generación de un interesante volumen de empleo pero unido a un fuerte desbalance social, manifestado en bajas remuneraciones relativas. Estos hechos ponen en el debate procesos regulatorios centrados en fortalecer las capacidades de los Estados para negociar con las IED factores compensatorios como transferencia tecnológica, mejoras en la capacidad productiva, desarrollo de competencias y fortalecimiento del aparato productivo y logístico, innovación y sostenibilidad de los modos productivos [16]. La Tabla 3 muestra la evolución del intercambio económico en el mundo impulsado por ZFPs, ZFPEs y zonas económicas especiales - ZEEs.

La Tabla 3, muestra como las exportaciones en todo el mundo han venido creciendo, p.e. América Latina en el periodo de los 10 años tuvo un crecimiento del 4.5% en sus exportaciones y su tendencia de importaciones se mantuvo en crecimiento constante aunque con un saldo a favor de 0.2% por debajo de las exportaciones, sin embargo el caso más representativo es China, donde el crecimiento exportador es de doble dígito, cerca del 12% y sus importaciones han crecido a menos de un 1% sustentada por la necesidad de uso de commodities como petróleo, carbón o chatarra. El detalle de la operación de las ZFPs en 2011 de Centro América se muestra en la Tabla 4.

Tabla 3.
Exportaciones e importaciones entre 2001 y 2010 de las principales regiones del mundo, impulsadas por el auge de las ZFPs y ZEEs.

Región	Exportaciones 2001-2010			Importaciones 2001-2010		
	US\$ MM	Vol (M, Tons)	% Crecimiento	US\$ MM	Vol (M, Tons)	% Crecimiento
MUNDO	10.1	4.9	5.1	9.1	6.1	3.0
América Latina y Caribe	12.4	7.8	4.5	10.6	6.4	4.3
EEUU	6.7	3.2	3.4	4.6	1.3	3.3
UE	11.0	4.9	6.1	8.0	5.3	2.7
Japón	11.5	2.6	8.9	7.4	5.8	1.7
Países Asiáticos en desarrollo	25.1	14.4	10.7	19.6	18.4	1.2
China	29.9	17.3	12.7	27.7	26.9	0.8

Fuente: Comisión Económica para América Latina y el Caribe (CEPAL), sobre la base de Naciones Unidas, Base de datos estadísticos sobre el comercio de mercaderías (COMTRADE) y CEPALSTAT [base de datos en línea] <http://websie.eclac.cl/sisgen/ConsultaIntegrada.asp/>

Tabla 4.

La generación de ZFPs y Empresas en Centro América

Factores y datos a 2011	Costa Rica	Salvador	Guatemala	Nicaragua	Panamá	Panamá zona libre colon	R. Dominicana	Total
# ZFPs y Em	256 Em	16 ZF, 200 Em	24 ZF, 270 Em	35 ZF, 696 Em	14 ZF, 94 Em	2960 Em	51 ZF, 586 Em	165 ZF, 5062 Em
IED Directa en ZFPs	470	ND	251	67	5	386	2.098	3.277
Exportaciones desde ZFPs	4.833	2.238	350	1.200	70	11	4.080	12.782
Empleo en ZFPs	58.012	70.321	17.000	99.506	2.729	30.000	121.000	398.568

Em: empresas. Cifras en Millones de dólares (USD)

Fuente: Elaboración propia con datos tomados de, SELA, Sistema Económico Latinoamericano y del Caribe. (2012). Influencia de las ZFPs en la diversificación productiva y la inserción de los países de América Latina y el Caribe. *I Conferencia de Autoridades Gubernamentales de ZFPs de América Latina y el Caribe* Cali, Colombia. Cali: SELA.

2.3. Evolución de las ZFPs e impacto en el empleo

En la década de los setenta sólo 29 países en el mundo habían avanzado en la creación de cerca de 665 ZFs [17]. En América Latina, en 1994, existían aproximadamente 66 zonas en 10 países [18]. Un estudio elaborado en 1998 por el SELA empezó a dilucidar un escenario prometedor con cifras y datos sobre el desarrollo de este esquema de producción y comercialización. Para el año de 1998 se encontraban registradas 850 ZFPs que generaban más de 27.000.000 de empleos alrededor del mundo. La CEPAL en 2002 hizo un estudio sobre el fenómeno de la ZF donde encontró que el número de países con ZFPs era de 116, para 2006 sobrepasaba los 130 y el número iniciando la segunda década del siglo XXI era de 135, esto debido principalmente a la consolidación económica de los países asiáticos y de Latinoamérica como economías emergentes y en desarrollo.

Los formatos de ZFs existentes también son muy diversos, entre estos se cuentan los modelos clásicos como los depósitos aduaneros, existentes en casi todos los países del continente, así como el modelo maquilador desarrollado e impulsado por México en varios países de Centroamérica, y nuevos y muy recientes modelos de ZFPE en el desarrollo de servicios, las cuales las encontramos en países como Colombia y Uruguay [3]. Actualmente se estima que se han creado más de 3.500 ZFs generando unos 66 millones de empleos de los cuales el 65% se encuentran operando en China.

Las ZFs, son consideradas una fuerte dinamizadora de empleos, sobre todo indirectos, esto se debe a la injerencia de las CAs en la instauración y desarrollo de la ZF. En países de la región, los impactos más significativos de empleo directo generado por la ZF se dan en países como R. Dominicana donde el 6.4% de la población económicamente activa trabaja en ZFs, otro país es Honduras con el 4.6%, pero en otras latitudes, como p.e. Emiratos Árabes se presenta una generación de empleo del 25%, Túnez 8% y Fiji el 10%. La experiencia muestra que el impacto en el empleo es mayor en naciones de población menor a los cinco millones de habitantes [17]. La Tabla 5 muestra la evolución e impacto en el empleo de las ZFPs:

Tabla 5.
Desarrollo de las ZFP en el mundo en los últimos 40 años.

	1975	1986	1995	2002	2007	2015
Número de países con ZFI	29	47	73	116	130	146
Número de ZFI	79	176	500	3000	3500	4300
China ejemplo aparte	N.D	N.D	N.D	13	26	187

ZFI: zona franca internacional.

Fuente: Singa (2007) y ANIF Asociación Nacional de Instituciones Financieras (2015).

Tabla 6.
Distribución de las ZFP en el mundo a 2015.

Región del mundo	Porcentaje de participación
Asia	43.6%
América del Norte	14.9%
América del Sur	6.9%
África	6.2%
Europa	6.1%
América Central	5.8%
Oriente Medio	2.8%

Fuente: AZFA, World Free Zones Org.

En cuanto a la diversificación del empleo, la ZFP lo llevan a cabo por medio de la extensión en el uso de mano de obra, conformación de redes de proveedores locales, actividades de ensamblaje parcial o total y desarrollos logísticos y de transporte. También se identifican beneficios en el desarrollo de servicios, empresas generadoras de investigación y conocimiento y tecnologías de la informática y las telecomunicaciones, desarrollo de software, call centers, operadores turísticos, consultoras, back office de sistemas, logística, desarrollo personal y profesional, entre otros.

China como líder ha utilizado sobre todo como modelo de ZF las Especial Economic Zones (EEZ); en segundo lugar encontramos a Norteamérica donde EE.UU y México, quienes gracias a sus tratados de integración, dinamizan de manera muy efectiva la simbiosis entre IED de parte de los Norteamericanos y las maquiladoras y procesadoras por parte de los Mexicanos. Latinoamérica participa con un significativo 12,7% del total, según datos de la Asociación de las zonas francas de las américas - AZFA a 2015 su distribución está contenida como muestra la Tabla 6.

La región asiática acumula actualmente cerca del 50% de las exportaciones mundiales de productos, impulsada por políticas de crecimiento enfocadas en la IED y la reconversión industrial, una creciente y económica mano de obra y una capacidad industrial sin par, en términos de economías de escala tanto productiva como logística [19]. La Tabla 7 muestra la distribución de ZFP en el mundo a 2014 y su impacto en el empleo.

Tabla 7.
Distribución de las ZFPs en el mundo año 2014

Región del Mundo	del ZFP	%	Puestos de trabajo	%	Empresas Instaladas	%
Norteamérica y Centroamérica	479	44.7	2.539.535	5.6	8.462	1.7
Asia	153	14.3	40.738.884	89.1	475.176	92.2
Europa Central y del Este	93	8,7	245.619	0,5	5.622	1,1
Caribe	93	8,7	220.803	0,5	1.000	0,2
Suramérica	68	6,3	205.225	0,5	7.645	1,5
Europa	67	6,3	50.830	0,1	5.363	1,0
África	64	6,0	877.777	1,0	3.862	0,8
Oriente Medio	38	3,5	691.397	1,5	7.429	1,4
Pacífico	16	1,5	141.089	0,3	787	1,1

Fuente: OIT, Organización Internacional del Trabajo, Manual sindical sobre ZF (2014) elaboración propia.

Tabla 8.
Evolución del empleo en el mundo asociado a la ZFP (Millones de personas)

2002	2007	2015
43	56	66

Fuente: Elaboración propia

Tabla 9.
Casos exitosos de exportaciones en relación con la generación de empleo en ZFPs del mundo en el último decenio.

#	Nº de ZFPs		Generación de empleos en miles		Exportaciones en US Millones	
1	China	187	China	50.000	China	145.000
2	Vietnam	185	Indonesia	6.000	Malasia	117.013
3	Hungría	160	México	1.300	Hong Kong	101.500
4	Costa Rica	139	Vietnam	950	Irán	37.289
5	México	109	Pakistán	888	Irlanda	32,500
6	R. Checa	92	Emiratos Árabes	552	R. Checa	68.262
7	Filipinas	83	Filipinas	545	India	49.000
8	R. Dominicana	58	Suráfrica	535	Argelia	39.423
9	Kenia	5	Tailandia	452	Argentina	36.478
10	Egipto	53	Ucrania	387	Filipinas	32.030

Fuente: Proexport 2012.

Las Tablas, 8 y 9, muestran cómo ha sido el crecimiento de empleo y las inversiones en el mundo y los países de la región latinoamericana.

Ya visto el agregado de regiones, la Tabla 9 presenta el Ranking de generación de empleo y exportaciones dentro de los países más destacados en el desarrollo de ZFPs en el mundo, 2012:

Como se muestra, las ZFP han sido grandes dinamizadores de empleo. En los países del sud este asiático el modelo ha sido muy funcional, a pesar que no representa un número destacado de empleos respecto a su densidad poblacional, en el caso de China este modelo le permite cumplir los requerimientos de la OMC en cuanto a prácticas comerciales, sin involucrar las relaciones políticas con el desarrollo del comercio. En América Latina se destacan México y Argentina.

Hay un auge de empresas de libre inversión IED que desarrollan procesos productivos por medio de las ZF, hoy en día las ZFP emplean directamente a más de un millón de empleados en el mundo. Los países en crecimiento, en la medida que han profundizado sus relaciones comerciales han encontrado en los TLCs un mecanismo ágil para dinamizar sus mercados y economías. Los países interesados seleccionan estratégicamente sus futuros aliados comerciales con el fin de lograr flujos de inversión y expansión del comercio mediante acuerdos de integración que les permita generar nuevos recursos mediante la captación de divisas [20].

2.4. Comercio internacional

Cerca de dos tercios de las exportaciones latinoamericanas tienen como destino países industrializados. Latinoamérica sigue vinculada de manera muy estrecha con EE.UU y lo que no logran colocar en este mercado lo viene orientando a abastecer los mercados asiáticos [19]. No obstante, el crecimiento económico de Latinoamérica se ha dado como consecuencia

Tabla 10.

Evolución de la estructura del comercio exterior 2000 y 2011 de América Latina y el Caribe. (En porcentajes del total de las exportaciones e importaciones de cada país o subregión.)

Región o país	Año 2000, Economías en desarrollo				Año 2011 Economías en desarrollo			
	Comparativo de exportaciones				Comparativo de exportaciones			
	Economías Industrializadas	Latinoamérica y el Caribe	Resto del mundo	% del PIB generados	Economías Industrializadas	Latinoamérica y el Caribe	Resto del mundo	% del PIB generados
América Latina el Caribe	75.0	16.4	8.6	25.0	55.5	19.4	25.1	44.5
América del Sur	56.8	28.4	14.8	43.2	38.2	24.6	37.2	61.8
Mercado Centro Americano	56.2	27.2	16.6	43.8	55.2	36.4	8.5	44.8
México	94.7	3.6	1.8	5.3	88.5	7.5	4.0	11.5
Caricom	66.2	24.9	8.9	33.8	64.2	27.5	8.3	35.8
Región o país	Comparativo de Importaciones				Comparativo de Importaciones			
	Economías Industrializadas	Latinoamérica y el Caribe	Resto del mundo	% de los egresos del PIB	Economías Industrializadas	Latinoamérica y el Caribe	Resto del mundo	% del PIB generados
América Latina el Caribe	70.0	16.5	13.5	30.0	50.6	20.8	28.6	49.4
América del Sur	54.0	29.2	16.8	46.0	39.5	27.4	37.2	61.8
Mercado Centro Americano	52.7	34.5	12.8	47.3	50.6	34.1	15.3	49.4
México	86.2	2.6	11.3	11.3	68.9	4.1	26.9	31.1
Caricom	67.0	25.5	7.5	33.0	55.0	32.6	12.5	45.0

Fuente: Comisión Económica para América Latina y el Caribe (CEPAL), sobre la base de Naciones Unidas, Base de datos estadísticos sobre el comercio de mercaderías (COMTRADE), y Conferencia de las Naciones Unidas sobre Comercio y Desarrollo (UNCTAD), base de datos UNCTADstat [en línea] <http://unctadstat.unctad.org/>

de la expansión industrial, principalmente de China, al ser la región uno de los principales proveedores de materias primas. El subcontinente ha venido en los últimos años desarrollando procesos económicos muy ligados al auge y fortalecimiento de los sistemas productivos derivados de las cadenas de valor, las cuales son auspiciadas por las empresas multinacionales y las instituciones de IED, su actividad recientemente incluye manufacturas de componentes necesarios para fabricar otros productos. Las ZFP juegan un papel muy importante ya que se convierten en actores de primera línea en los procesos de integración productiva e industrial de las cadenas de valor, industrias como la electrónica, la de bienes manufacturados, la automotriz o la del vestuario están generando tendencias, donde la producción ya no se focaliza en un solo lugar sino que su producción es modular e integral, aprovechando la variedad de ventajas competitivas que regiones o Estados ofrecen. Así mismo, los servicios conexos como repuestos, insumos, posventa, sistemas, comercialización y finanzas también están siendo descentralizados y clusterizados con el fin de hacer más rentables desde diversas ópticas las operaciones productivas. La Tabla 10 presenta la evolución de la estructura del comercio exterior 2000 y 2011 de América Latina y el Caribe:

Como se observa en la Tabla 10, es creciente la participación de las importaciones en el desarrollo de la región, que aumentó 19.4 puntos porcentuales en el lapso comprendido entre 2001 y 2011, pasando de 30% a 49.4% del total. Esto es el reflejo de la dinámica de los mercados, influenciados fuertemente por la figura de los TLCs y el surgimiento de Alianzas Comerciales Regionales como Asia-Pacífico; en este caso se dio continuidad a la inercia favorable que antes de esta situación que ya se representaba desde inicios de siglo asociada a un 47% de las exportaciones del subcontinente [19]. Así mismo el proceso de exportaciones también se dinamizó en este mismo lapso de tiempo, se

observa que la dinámica económica de la generación de ingresos avanzó, donde el rubro por este concepto paso del 25% de los ingresos en promedio hasta generar el 44,5% del PIB de los países de la región. Así mismo Suramérica tuvo una tendencia similar de crecimiento en la balanza comercial a Latinoamérica en conjunto, el crecimiento de las exportaciones entre los dos periodos de tiempo fue de 18% y las importaciones en el mismo periodo aumentó en 20.5%, lo que hace que la balanza siga siendo de déficit comercial pese a que la tendencia exportadora sea creciente.

2.5. Elementos desarrolladores de la ZFPs en la región Latinoamericana.

Las ZFs se destacan hoy en día como base y fundamento para el desarrollo de muchas economías a nivel mundial, países como R. Dominicana, desarrollan su producción económica principalmente mediante dos rubros, el primero es el turismo y el segundo el desarrollo de la ZF de servicios establecidas en el país, por otra parte en países como México, Colombia o Chile, con economías más diversas y robustas, incorporan a la ZF como parte del proceso de producción económica y le otorgan una prioridad fundamental al promocionarlas. Los Estados deben establecer para las ZFPs y ZEEs un sistema regulatorio meticuloso aunque práctico que incluye: estimación del modelo de negocio en un contexto prospectivo, y del funcionamiento del modelo; procedimientos aduaneros, plazos de entrega de mercancía, coberturas y beneficios, entre otros tal y como lo sustenta [20].

Para que el modelo de ZFP, sea productivo, es necesario que se mantenga actualizado e incorpore tecnologías y conocimientos surgidos de las tendencias comerciales y empresariales contemporáneas. La estrategia consiste en integrarse a las cadenas de valor, iniciando con ensamblajes básicos y sencillos, para ir generando procesos de producción

Tabla 11.

Componentes prioritarios para el desarrollo de las ZFP en Latinoamérica

País Exportador	Total - EEUU	Resto del mundo	Población	Per cápita exporta do
Costa Rica	10.111.100.492	8.769.728.57	4.636.348	2.181
México	262.670.975.073	208.491.103.951	114.975.406	2.285
Honduras	4.456.848.357	3.747.028.382	8.296.693	537
R. Dominicana	4.154.575.088	4.000.104.194	10.088.598	412
Chile	9.169.821.460	6.328.171.153	17.067.369	537
Salvador	2.481.461.924	2.234.996.876	6.090.646	407
Nicaragua	2.607.154.559	2.085.942.811	5.727.707	455
Guatemala	4.135.509.852	2.204.461.562	14.099.032	293
Perú	6.152.813.259	3.585.277.034	29.549.517	208
Colombia	22.390.928.185	5.105.192.192	46.044.601	486
Panamá	388.090.146	277.588.052	3.517.000	110
*Cafta Caribe	27.946.650.272	23.042.262.396	48.939.024	571

Fuente: Elaboración propia, inspirado en la metodología de Humprey y Smith, 2002.

fraccionados que van incorporando tecnología y personal cualificado para contribuir finalmente al desarrollo de componentes esenciales con los que logren desarrollar procesos productivos y competitivos desde el punto de vista de estructura de costos, rentabilidad y competitividad [21].

En este sentido, [22] proponen una metodología de evolución, donde el modelo de las ZFP en Latinoamérica puede generar derroteros de productividad y competitividad acorde a las exigencias del mercado internacional. La propuesta se basa en la incorporación de dos elementos fundamentales como objetivos de desarrollo: la Innovación y el desarrollo tecnológico y productivo derivado de la transferencia tecnológica, lo que se conjuga con los tres pilares necesarios para establecer la estructura de crecimiento de las ZFP: integración productiva, mejoramiento de los modelos de comunicación y políticas fiscales y monetarias estables, que deben dar como resultado una ruta de evolución que asegure el crecimiento y desarrollo constante del modelo productivo, tal como está estipulado en la Tabla 11.

El mejoramiento intersectorial que puede facilitar las ZFPs consiste en el desarrollo de encadenamientos fuertes derivados de las sinergias establecidas entre los inversores, bien sean mediante IED, o a través de proveedores locales, o en colaboración con el Estado. Según [22], lo que se busca es un beneficio común para el inversor, promoción de alianzas estratégicas con agentes productivos locales; que permita optimizar sus estructuras de costos, mano de obra, la infraestructura local y la comercialización de excedentes de producción. La función central del Estado en este proceso es la de intervenir en cada uno de los agentes y segmentos de las CAs con el fin de optimizar de manera estratégica los procesos productivos de las empresas [23], adicionalmente tiene la responsabilidad de promover la legislación en materia comercial y la protección de derechos de autor y patentes de productos derivados de investigación. Las empresas por su parte se deben enfocar en el fomento de procesos de transferencia de tecnológica y de inteligencia de mercado que les brinde la oportunidad a los desarrolladores locales de mejorar sus capacidades de diseño e innovación productiva. Por otro lado, se necesitará de la incorporación de nuevos talentos fortalecidos en conocimiento y apoyados con fuertes componentes tecnológicos, para generar actividades de valor a las ZFI, lo que redundará en la generación de soluciones de mercado.

Tabla 12.

Per cápita exportador de manufacturas de América Latina y el Caribe

Componentes prioritarios	Innovación	Desarrollo Tecnológico y Productivo
La implementación de los componentes se basa en tres pilares fundamentales	Integración productiva global	Desarrollo, comunicaciones y conectividad
La combinación de factores y los pilares, determina la siguiente línea de evolución en las ZFP	Punto base: Producción básica, mano de obra no calificada	Mejora de los procesos productivos
		Mejora de las funciones productivas e intersectoriales

Cifras en Millones de Dólares

* TLC EEUU, Centroamérica y República Dominicana.

Fuente: Elaboración propia con datos tomados de, SELA, Sistema Económico Latinoamericano y del Caribe. (2012). Influencia de las ZFPs en la diversificación productiva y la inserción de los países de América Latina y el Caribe. *1 Conferencia de Autoridades Gubernamentales de ZFPs de América Latina y el Caribe Cali, Colombia*. Cali: SELA.

Las ZFPs han servido como catalizador en el desarrollo de las relaciones comerciales de Latinoamérica con EEUU. Para el año 2012 diez países de región contaban con TLC con esta nación. Los EEUU no solo fungen como comprador de productos, sino también como regulador de las dinámicas de mercado de los países de la región y generador de los capitales de IED que dinamizan las economías locales [17]. La Tabla 12 referencia los diversos niveles per cápita exportadores 2012 de los países de América Latina en su relación con EEUU.

México es el país de la región que presenta mayor per cápita exportador para 2012 con un valor per cápita de US\$2.285, le sigue Costa Rica con US\$2.182 y lejanamente el resto de países con menores diferencias entre ellos.

3. Resultados y Conclusiones

En los últimos cinco lustros, el desarrollo y consolidación de la ZF en la región latinoamericana ha permitido que este instrumento de generación de comercio y desarrollo industrial se haya convertido en un gran dinamizador del empleo, transferencia y adquisición de tecnología, diversificación productiva y de la ampliación de la oferta exportable, gracias a la apertura de nuevos mercados e inserción en el mercado internacional. Para los países en vía de desarrollo la figura de las ZFP es clave para la consolidación de sus economías, debido a que por medio de estas aseguran un significativo flujo de capital proveniente de la IED y orientan sus esquemas de producción a la generación de exportaciones. Con ésta estrategia estas economías son más atractivas para la IED. También se retrotrae un concepto de la CZFA sobre el papel que cumplen estas figuras productivas “las ZF son instrumentos de política comercial que tiene el efecto de expandir y modernizar la economía por medio del efecto de la expansión del capital, transferencia tecnológica, proveedor de servicios logísticos y generador de empleo” [24].

Como lo explica [25], son los países emergentes quienes recurren a la figura de la ZFP como medio de crecimiento y

expansión de sus economías a pesar de la oposición de los gobiernos de los países desarrollados, la razón, adquieren competencias que los hacen fuertes competidores en el mercado creando inmunidad a los efectos de los subsidios y subvenciones de estos últimos países a sus productores.

La recepción de *utilities* o bienes semi-manufacturados y transferencia tecnológica por parte de las IED, para integrar a las ZFP en sus procesos productivos, es considerada parte fundamental para la redistribución de recursos, ya que facilita el camino para el intercambio comercial y las empresas inversoras, sin importar si es IED o inversión local, ven rentabilizados sus capitales al invertir en la ZFP; debido a que pueden utilizar mejor los recursos, replantear sus procesos productivos con miras a las exportaciones o extensión de las redes de intercambio mundial y fabricar productos con componentes ensamblados en diversas latitudes, lo que en definitiva les genera competitividad económica y de mercado. El enclave permite que las transacciones se realicen de manera más expedita, sin necesidad de verse en la obligación de compartir sus utilidades con los países receptores, evitando el pago de cargas impositivas; en síntesis, sus filiales tienen más radio de acción al poder intercambiar bienes, servicios o insumos de forma ágil y sin las trabas que determina la nacionalización de estos elementos productivos.

Uno de las más importantes misiones de la ZFP es la generación de empleos. Al respecto, para Costa Rica y México el modelo de desarrollo de ZFP ha sido tomado como una apuesta fuerte en su entorno económico, el modelo productivo mexicano está basado en el sistema de maquilas, el cual genera altos índices de empleo, mientras que el de Costa Rica está enfocado en el desarrollo de servicios, en estos países el modelo se asocia a estrategia Estatal. En países como México, Rusia y China, la ZFP, ha permitido generar nuevas oportunidades de negocio, en el mercado de los servicios, las tecnologías de la informática y comunicaciones. Pese a que en algunos casos, debido a su sofisticación, no se generan amplias plazas de mercado laboral [26]. Con todo, las ZFPs en la región no se destacan de manera especial en su nivel de empleabilidad, debido al tamaño de las operaciones y franquicias, otros factores como falta de estímulo laboral para trabajar en este tipo de negocios pueden también explicar este hecho. La razón más importante es la evidente falta de atención al modelo en la mayoría de los países de la región como estrategia de empleo, no se evidencia que el Estado tenga una atención especial al modelo y su fomento.

Las ZFPs y el país establecen un fuerte vínculo por el cual el país huésped recibe las divisas generadas por la transferencia de tecnología, desarrollo de capital humano, nacionalización de mercancía para abastecer el mercado local y toda actividad que genere algún valor, así la ZFP se puede ver como el elemento articulador dentro de la CA. No obstante, para que el modelo funcione de una manera creciente y las ZFP sean realmente competitivas y aporten a discreción a las necesidades, hay que desarrollar un proceso productivo ascendente, el cual se puede contemplar desde cuatro aspectos: 1. inicialmente se tiene la producción donde priman los ensamblajes con mano de obra poco calificada, 2. su evolución al desarrollo diferenciado, 3. especialización de la producción, y por último, 4. fabricación de componentes críticos, los pasos se dan como parte del proceso de

diversificación productiva que los diferentes países de la región latinoamericana adoptan como patrones de acumulación económica, sector de los servicios en el Caribe, desarrollo de los bienes primarios en Suramérica y México y Centroamérica como dedicados a la actividad maquiladora [27].

[28] Explican que si bien es cierto que los inversores locales toman cada vez más asiento en el desarrollo de las ZFP, son las IED las que manejan el gran flujo de recursos invertidos en estos escenarios productivos. Las filiales de estas organizaciones tienen a su consideración el poder de usar a discreción las “Ventajas de Propiedad”, que se determinan del uso de las tecnologías y los procesos productivos, así como de BPM (*business process management*) y desarrollos de mercado, que se derivan de la I+D de las mismas empresas proporcionada por sus casas matrices. Esto les proporcionan una ventaja competitiva desde el ámbito de la producción con la competencia local, ya que al establecer redes de comercio con proveedores locales, comercializar productos con tecnología de punta y a precio más económico y pueden fácilmente entrar a manejar las corrientes de comercio de los países huéspedes, por ello esto debe ser compensando con transferencia tecnológica, desarrollo de infraestructura y dinámicas de mercado más activo. Esto se refleja en la activación de las exportaciones por parte de país huésped, quien también se beneficia con la captación de nuevas divisas.

La estrategia tradicional de ZFPs requiere de procesos de soporte para mantener la dinámica en el tiempo, fundamentalmente el desarrollo de mano de obra calificada, el desarrollo de una base estratégica inversión en educación y ciencia, tecnología en innovación para el desarrollo de la capacidad de diseño tecnológico, en síntesis medidas asociadas a paradigmas de desarrollo de países desarrollados.

La rebaja de aranceles determinada por los TLCs tiene una incidencia positiva en la optimización de las cadenas de suministro. En la ZFP este efecto es mucho más notorio debido a los regímenes especiales de los que goza esta figura económica. Este proceso de avance está ligado a cuatro componentes principales que inciden directamente en el mejoramiento de los productos que se da desde el término de *Upgrading* el cual proponen [29] como: 1. la innovación y el aumento del valor agregado de los productos, 2. involucrar etapas del desarrollo del producto y el aprendizaje comercial, 3. el saber qué hacer, a los productos para innovar a una velocidad mayor que la de sus competidores y 4. Mejorar las capacidades de producción y desarrollo de las organizaciones para avanzar en la rentabilidad.

Los centros de producción industrial, incluidos las ZFPs, deben ser ubicados en lugares geográficos estratégicos, donde se debe conjugar óptimamente los procesos productivos y logísticos. Este proceso de decisión suele ser complejo por la cantidad de alternativas propias del estado de globalización de la economía y los negocios [30].

La IED está amenazada en la región por cambio en la política económica, la latina, que genera menos confianza, y estadounidense, por el incremento de la tasa de colocación de sus bonos federales, lo que en conjunto ha hecho que se vaya desplazando a este país desde finales de 2014.

4. Recomendaciones

En las ZFP se conjugan elementos importantes desde la óptica de la productividad. Lo que buscan los países al instaurar estas figuras productivas es por lo general, llamar la atención de la inversión; ésta se debe destinar para generar nuevos puestos de trabajo, hacer transferencia tecnológica y de conocimiento a entes locales y población local, e incentivar las exportaciones, con especial atención a las que son no tradicionales.

El desarrollo de las zonas de libre comercio, zonas industriales especiales y ZF de exportación, requiere de una estrategia particular para cada uno de los países en vías de desarrollo. El propósito consiste en generar un modelo de negocio que aproveche los recursos naturales de la región para ir adoptando y adquiriendo tecnología y conocimiento que promueva la capacitación de los recursos humanos y así facilite el desarrollo de procesos de manufactura con estándares de competitividad internacional, para en definitiva facilitar el acceso a los mercados internacionales.

El desarrollo del modelo de ZF implica que para que sea más productivo debe incorporar también elementos de mejora de la calidad de vida de los trabajadores manifestados en: capacitación y especialización productiva y mejores salarios [22].

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Combined control of a flywheel energy storage system and a vanadium redox flow battery for wind energy applications in microgrids

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Abstract

The incorporation of wind generation in microgrids is growing progressively. This integration can introduce problems in the dynamics and power quality of the electrical system due to the wind fluctuations. This work proposes a controller composed by a power conditioning system (PCS), a Flywheel Energy Storage System (FESS) and a Vanadium Redox Flow Battery (VRFB) to palliate problems introduced by wind generation in microgrids. A model of the PCS/FESS-VRFB controller is presented and a method to control the power exchanged between the controller and the power system is suggested. The control method has two modes, namely: power levelling and frequency control. The performance of the PCS/FESS-VRFB controller is studied when it works with wind power generation in the microgrid through simulation tests. Results demonstrate suitable performance of the control methods and high effectiveness to level the wind power fluctuations and to provide support to the frequency control of the microgrid.

Keywords: flywheel energy storage system; vanadium redox flow battery; microgrid; wind power generation; power levelling; frequency control.

Control combinado de un sistema de almacenamiento de energía flywheel y una batería de flujo redox de vanadio para aplicaciones de energía eólica en microrredes

Resumen

La incorporación de potencia eólica en microrredes está creciendo progresivamente. Esta integración puede introducir problemas en la dinámica y calidad de potencia del sistema eléctrico debido a fluctuaciones del viento. Este trabajo propone un controlador compuesto por un sistema de acondicionamiento de potencia (PCS), un almacenador flywheel (FESS) y una batería de flujo redox de vanadio (VRFB) para mitigar problemas introducidos por la generación eólica en microrredes. Se presenta un modelo del PCS/FESS-VRFB y se propone un método para controlar la potencia intercambiada entre el controlador y la red eléctrica. El método tiene dos modos: nivelación de potencia y control de frecuencia. A través de simulaciones, se estudia el desempeño del PCS/FESS-VRFB cuando opera con generación eólica en microrredes. Los resultados demuestran un adecuado desempeño del método propuesto y una alta efectividad para nivelar las fluctuaciones de potencia eólica y proveer soporte para el control de frecuencia de la microrred.

Palabras clave: sistema de almacenamiento de energía flywheel; batería de flujo redox de vanadio; microrred; generación de potencia eólica; nivelación de potencia; control de frecuencia.

1. Introduction

The percentage of penetration of wind power generation in grid-tied microgrids (MGs) is growing [1-3]. The type of

generation system implemented by wind turbines and the fluctuating nature of the wind can have a negative effect on the dynamic security and the power quality of the MG [4-7]. To mitigate these problems, new energy storage devices

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arise as an alternative with the purpose of compensating the power fluctuations. These energy storage systems can swiftly provide the MG with both reactive and active power simultaneously, and consequently serve to enhance the MG dynamic security and power quality [8]. There are numerous storage devices, some of which will be more convenient than others, depending on the application [7-11].

Among modern energy storage devices, Flywheel Energy Storage System (FESS) and Vanadium Redox Flow Battery (VRFB) are some of the most promising technologies. Both storage devices have quick response time, high energy efficiency, and long lifetimes. FESS has power rating in the order of MWs, and discharge time in the order of minutes. FESS stand out for their low capital cost per unit power (around 700 US\$/kW); nevertheless, it has a high capital cost per unit energy (around 2000 US\$/kWh) [10-13]. On the other hand, VRFB has power rating in the order of MWs, and discharge time in the order of hours. In contrast to FESS, VRFB is remarkable for its low capital cost per unit energy (approximately 600 US\$/kWh) and its high capital cost per unit power (2500 US\$/kW) [10,11,13].

Many solutions using FESS or VRFB devices have been proposed in the bibliography either to smooth wind power fluctuations or to provide ancillary services [14-22]. Reference [14] proposes a novel control strategy using flywheel energy storage to smooth the power injected by wind generators. In [15], a direct torque control for an induction machine used in flywheel storage is proposed to compensate the power fluctuations of a variable-speed wind generator. Reference [16] proposes a multi-level control for a controller composed by a DSTATCOM and a FESS in order to enhance the integration of wind power generation in electrical networks. In [17], control strategies using a fuzzy logic supervisor with FESS are developed in order to smooth the rapid fluctuations of wind power and to provide ancillary services. Reference [18] presents a control strategy for the frequency regulation in a wind-diesel powered MG using flywheels and fuel cells. In [19], a VRFB is proposed to improve the power quality and the stability of the power system that include wind power generation. Reference [20] highlights the alternative to spilling wind to provide frequency response capability using wind farm with VRFB. Reference [21] proposes a methodology for the economic optimization of the sizing of a VRFB whilst enhancing the participation of wind power plants in network primary frequency control support. In [22], a thyristor-based flexible ac transmission system is proposed and developed for controlling the exchange of active power flow between the VRFB and the grid in order to compensate the wind power variations generated by DFIG turbines. Although the papers mentioned present practical solutions to improve the integration of wind power generation using FESS or VRFB devices, they do not use both devices combined taking advantage of the better characteristics of each device. Nor do they perform a combined active power control in order to level the power oscillations of wind generation and provide ancillary services so as to participate in frequency control.

Based on the previous discussion, this work proposes the use of an integrated controller constituted by a FESS and a VRFB for better integration of wind power systems in

microgrids. This integrated controller also includes a power conditioning system (PCS) in order to connect the FESS-VRFB to the ac power system. To implement the PCS/FESS-VRFB controller, requires administration of the energy stored in the FESS and VRFB devices so that these devices always have the capacity to deliver or store energy. In this manner, a function that can efficiently manage the stored energy is essential. This function, carried out via a control strategy for the active power of the PCS/FESS-VRFB, has to accomplish two aims simultaneously: smooth the wind power fluctuations injected into the MG effecting a suitable use of the stored energy, and assist the frequency control in case of perturbations in the MG.

The objective of this work is to elaborate an effective control methodology of the controller proposed both to level the power fluctuations injected by wind generators in the MG and to contribute to the frequency control of the system in case of perturbations in the MG. For this purpose, while considering the characteristics and costs of each storage device, a control is proposed so that the FESS works applying frequency control when important faults occur in the MG (the storage device requires low energy and much power); and the VRFB works effecting power levelling (the storage device requires much energy and low power). The control method proposed includes two control modes of the PCS/FESS-VRFB controller, namely: power levelling (carried out by the VRFB), and frequency control (carried out by the FESS). For both proposed control modes, the charge status of each storage system is considered. The dynamic performance of the developed control method and its effect on the operation of the MG is validated by computer simulation the MATLAB/Simulink, by using SimPowerSystems and C++ codes.

2. Modelling of the PCS/FESS-VRFB controller

A model of the PCS/FESS-VRFB controller proposed for this study consists mainly of the PCS, the FESS and the VRFB. The PCS is the power electronic interface between the FESS-VRFB and the ac electric utility grid, pointing at reaching three aims: one is to convert electric power from the FESS to the ac grid, another is to convert the dc voltage of the VRFB to the ac grid, and the final one is to efficiently load/unload the FESS and VRFB storages. The diagram of the proposed modelling of the PCS/FESS-VRFB controller is shown in Fig. 1.

The PCS proposed is integrated by a back-to-back ac/dc/ac converter (composed of two voltage source inverters). The proposed inverter structure to the ac/dc/ac converter is based on a two-level six-pulse topology. Moreover, it uses sinusoidal pulse width modulation techniques to control the output voltage control of the VSI. The chopper consists of a buck-boost converter, which is commonly used when the magnitude of two dc bus voltages is close to each other and the voltage ratio is smaller or greater than unity and it does not vary significantly. The power exchange between the flywheel and the ac/dc/ac converter is carried out through a permanent magnet synchronous machine (PMSM). The flywheel is modelled as an additional mass coupled to the rotor shaft of the PMSM

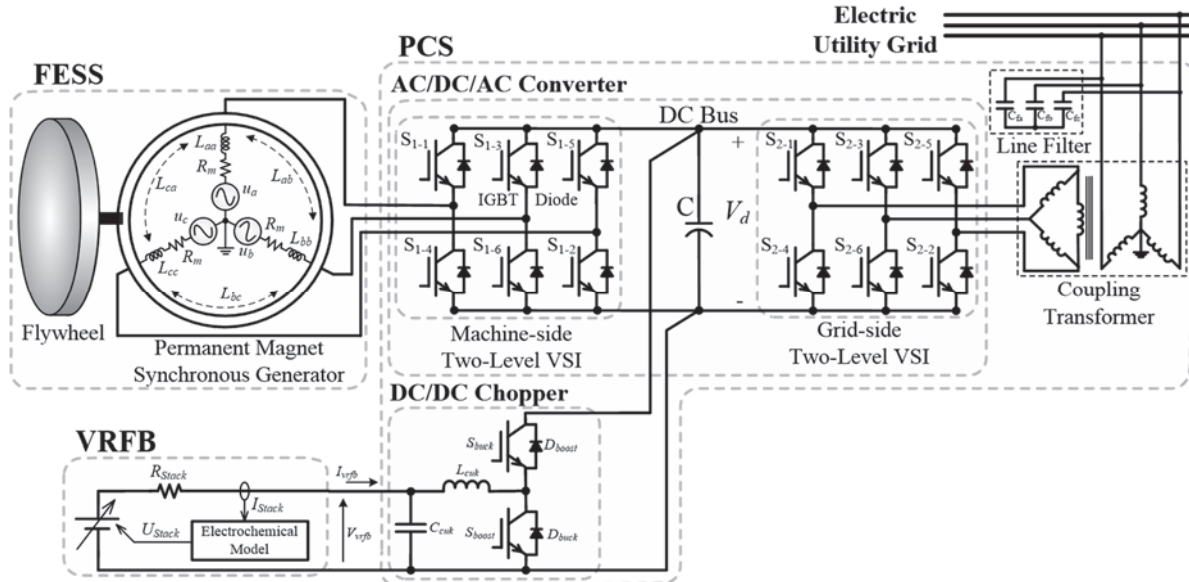


Figure 1. Model of the proposed PCS/FESS-VRFB controller.
Source: Authors

[23]. The FESS model with its PCS is comprehensively analysed in [16]. The VRFB model is composed of two parts: the stack model (electrochemical model), and the mechanical model. In the stack model, the terminal VRFB current (I_{VRFB}) determines the stack current (I_{stack}) and consequently, the terminal stack voltage (U_{stack}) and the state of charge (soc) of the electrolyte. In the mechanical model, the external control system sets the flow rate that produces a pressure drop in the hydraulic system. The VRFB model with its PCS is comprehensively analysed in [22].

3. Control system

The control proposed for the PCS/FESS-VRFB controller is divided into three: the Chopper control, the machine-side VSI control, and the grid-side VSI control. For each control, a multi-level scheme is suggested [24,25]. The multi-level control scheme of the chopper is divided into two levels: internal and middle levels; and the multi-level schemes of the machine-side VSI and the grid-side VSI are divided into three levels: internal, middle and external levels. The control system of the PCS/FESS-VRFB controller is shown in Fig. 2. The control algorithm for the flywheel energy storage is fully developed in [16], and for the VRFB and chopper in [22]. Only the external level of the grid-side VSI control (bottom, right-hand corner of Fig. 2) is presented below which is the main contribution of this work.

The external level control of the grid-side VSI is in charge for establishing the power exchange between the grid-side VSI and the electric power system [16,24]. The external level control has the following modes of operation of the PCS/FESS-VRFB: power levelling (PL), frequency control (FC), and voltage control (VC). The PCS/FESS-VRFB controller constantly works in VC and PL modes with the VRFB connected and the FESS in standby; enhancing the power quality generated by wind power generators. When

significant frequency deviations take place, the FC mode is active, helping to recuperate the rated system frequency and thus improving the grid security. In the FC mode, the FESS is activated. In this work, only the PL and FC modes are developed, which are the core of the contribution.

3.1. Power levelling

The objective of controlling the active power stored or generated by the storage system (mainly the VRFB) is to level the fluctuations of wind power and to manage the energy stored properly so that the VRFB storage device always has capacity to deliver or store energy. Therefore, the control is designed considering the wind power generation and the state of charge of the VRFB. Fig. 2 (PL block) shows the structure of the power levelling control.

The first step to enable the control is to level the power of the wind generators. This is carried out by eliminating the turbulent component (P_t) of the wind power (PWG). For this, a low-pass filter with a cut-off frequency at 1 cycle/h is used to obtain the diurnal and synoptic component of the wind power (P_{ds}) [22]. Then, the P_{ds} is passed by a regulator to obtain the levelling power regulated. The purpose of this regulator is to compute the value of a regulation power, P_{reg} (desired power from WGs plus VRFB). Finally, the power generated by wind system, PWG, is subtracted from the P_{reg} , and thus the reference power, P_{ref2} , is obtained. This P_{ref2} must either be stored or generated by the VRFB.

The state of charge, soc , and the filtered value of wind power generation, P_{ds} , are the inputs of the regulator. The regulator is built according to the following rules:

- 1) If the soc of the VRFB is exhausted, then the charge of the VRFB will be prioritized.
- 2) If the soc of the VRFB is almost complete, then the discharge of the VRFB (power generation) will be prioritized.

- 3) If the *soc* of the VRFB is half, then either charge or discharge of the VRFB will be not prioritized. The electric power system receives the wind power fluctuations levelled by the VRFB.

Using eq. (1), the regulator calculates the P_{reg} , as a function of the *soc* and P_{ds} . Moreover, the regulator is done while taking into account that the *soc* can only work between 0.2 and 0.8 of the maximum *soc* [22]. Fig. 3 shows the evolution of P_{reg} according to the *soc* and the P_{ds} .

$$P_{reg} = \frac{5}{6}soc + \frac{P_{ds}}{2} - \frac{1}{6} \quad (1)$$

3.2. Frequency control

The frequency control is in charge of establishing the power exchange between the storage system (mainly the FESS) and the electric power system when faults in the system cause significant deviations in the frequency. The frequency control is responsible for minimizing the duration and magnitude of system disturbances by absorbing power imbalances caused by the fault, with the purpose of keeping the system frequency higher than the minimum level. Fig. 2 shows the structure of the frequency control (FC block).

The measured frequency of the system, f_s , is compared with a reference frequency, f_r . A dead-band block (DB) is used with the aim of determining the entry of the FESS in the frequency control of the electric power system. The output current signal i_{prl} depicts the active current flow that the FESS needs to inject for compensating the frequency shift of the electrical system.

In accordance with the FC mode, the FESS should be in some measure charged at a specific rating to permit power to be injected or absorbed into or from the grid at any time. This allows for the balancing negative and positive power variations in the electrical system. The level of charge of the FESS is controlled by considering the power flow in the line that connects the MG to the electric utility grid (P_{grid} in Fig. 2). If P_{grid} goes from the electric utility grid to the PCC, a disconnection of the line causes a decrease in the frequency of the MG (the FESS should be charged so that energy can be injected); and if P_{grid} goes from the PCC to the electric utility grid, a disconnection of the line causes an increase in the frequency of the MG (the FESS should be discharged so that energy can be absorbed). Therefore, the P_{grid} determines the initial state of charge (ω_{r_in}) of the FESS. The control schematized in Fig. 4 is used to calculate the ω_{r_in} . The ω_{r_in} is cancelled when frequency deviation exceeds the dead-band value in order to prioritize the frequency regulation, as described in Fig. 2 with the state 0/1 outgoing from the DB block.

The control schematized in Fig. 4 is designed with the following criteria:

- 1) If P_{grid} goes from the electric utility grid to PCC, the FESS must be charged to the maximum charge to provide energy in case the frequency drops down by the disconnection of the line. In this case, 0.9 of the maximum value of the state of charge is adopted.
- 2) If P_{grid} goes from the PCC to electric utility grid, the FESS must be charged to the minimum charge to absorb

energy in case of the frequency rises by the disconnection of the line. In this case, 0.1 of the maximum value of the state of charge is adopted.

- 3) If P_{grid} is close to zero (for one side or another), the state of charge varies linearly with P_{grid} , among adopted values ± 0.2 of the maximum power of the controller. 0.2 P_{c_max} is chosen due to: A) at lower values, the FESS could go from maximum to minimum load (and vice versa) extremely quickly, and B) at higher values, the FESS could be working constantly since the reference is always changing. In addition, a low pass filter (LPF2) is placed at the output of this control block to limit abrupt changes in the reference due to variations when the power is close to zero.

4. Test power system

The test power system employed to validate the proposed control methodology of the PCS/FESS-VRFB controller for enhancing the incorporation of wind power generators in MGs is shown in Fig. 5. This electrical network implements a MG connected through a 20 km transmission line and a transformer to a bulk power system represented by a single machine-infinite bus type system. The MG consists of different distributed energy resource units (distributed generation based on renewable and fossil fuels and the advanced PCS/FESS-VRFB controller) and loads.

The distributed generation based on renewable resources consists of a wind farm integrated by three rows of wind turbines with three turbines per row. The technology used by each wind turbine corresponds to a variable speed wind turbine with full-scale frequency converter. The rated power of the wind farm is 9MW (each wind turbine has 1 MW rated power). The distributed generation based on fossil fuel (50 MVA rated power) consists of a dispatchable unit powered by multi-stage tandem compound steam turbine and includes a speed governor and a voltage regulator. All loads are grouped at bus 5. The proposed controller is placed at bus 2, representing the point of common coupling of the wind farm (PCC-WF) to the rest of the ac microgrid, and includes a ± 10 MVA/750 V dc bus PCS, a 6 MW/60 MJ FESS system, and a 2 MW/3600 MJ VRFB system. Full test system data are included in [16,17,22].

The testing of the control proposed for the PCS/FESS-VRFB controller in grid-tied operation is done through two case studies that demand a high dynamic response of the controller. The first case analyses the behaviour of the control of the PCS/FESS-VRFB when a real profile of wind speed is established to the wind turbines so that the PCS/FESS-VRFB controller operates continuously by delivering and storing energy. In this case, the behaviour of the PL control mode and the operation of the VRFB is mainly shown. In the second case, the PCS/FESS-VRFB controller is tested when external perturbations are imposed on the bulk power system, so that the microgrid is changed to islanded operation mode and major frequency shifts occur. In this case, the behaviour of the FC control mode and the operation of the FESS are mainly observed.

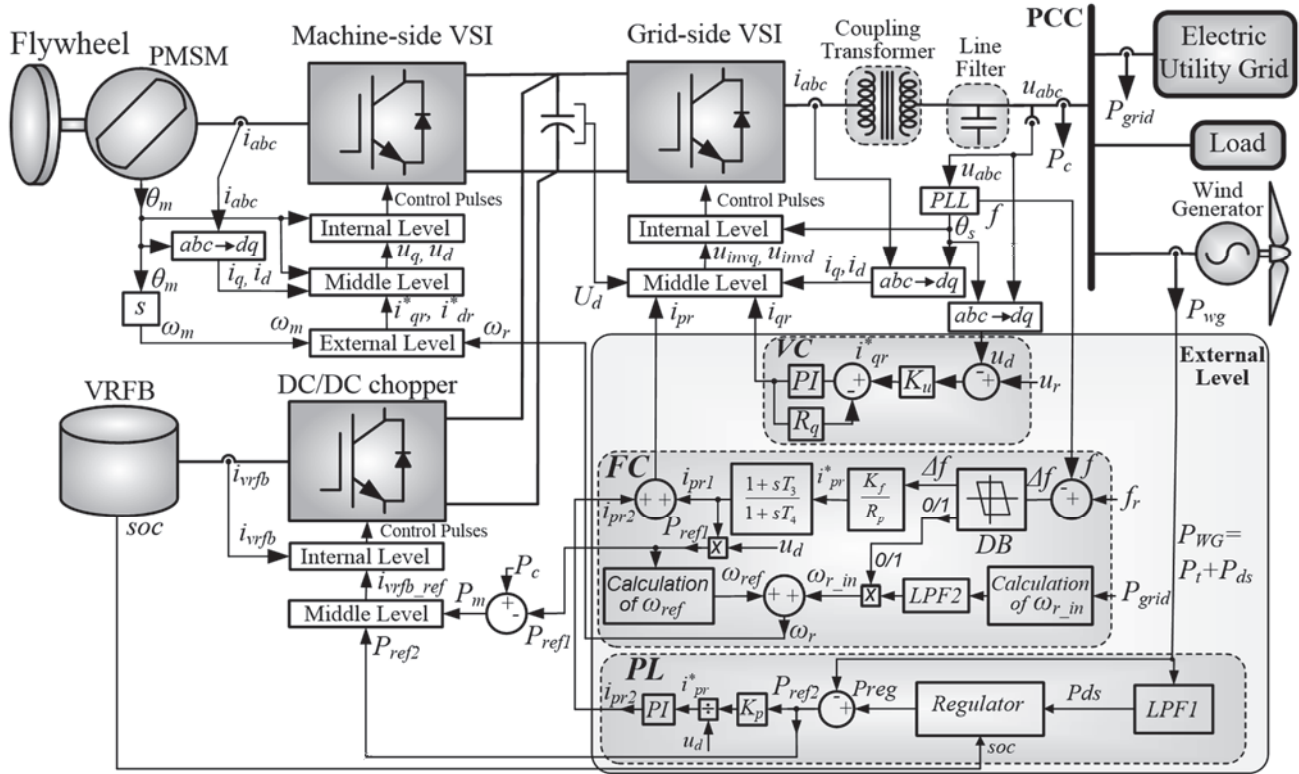


Figure 2. Control structure of the PCS/FESS-VRFB controller.
Source: Authors

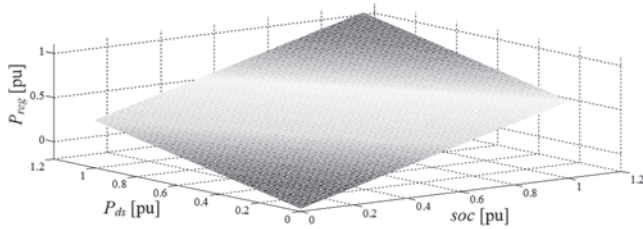


Figure 3. P_{reg} against soc and P_{ds} , obtained with the proposed regulator.
Source: Authors

5. Digital simulation results

5.1. PCS/FESS-VRFB performance analysis working in PL mode

For this case study, the test power system shown in Fig. 5 is used. A suitable profile for fluctuation of the wind speed is applied. This profile has a variable mean value of the wind speed, so that the wind farm (WF) operates near the minimum and maximum power. The active power flow for the system WF plus PCS/FESS-VRFB, with the PCS/FESS-VRFB controller unplugged and plugged, is shown in Fig. 6(a). It is observed how the PCS/FESS-VRFB controller reduces the wind power fluctuations with the proposed PL control mode, avoiding these perturbations from being injected into the electric power system.

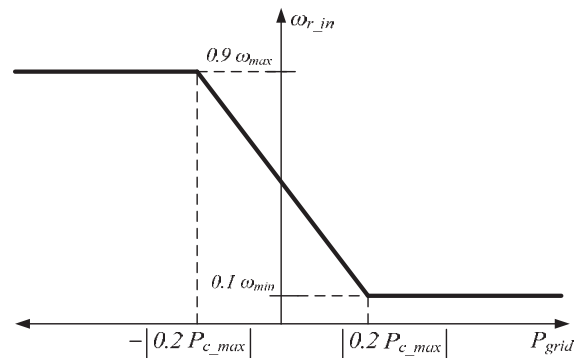


Figure 4. Calculation of the initial state of charge of the FESS.
Source: Authors

In this case, the VRFB is working on the PL control mode, and the FESS device is on stand-by. Fig. 6(b) shows the active power injected by the VRFB device. It can be noted that the rapid active power variations injected by the VRFB device aptly counteract the wind power fluctuations. Besides, the PCS/FESS-VRFB controller notably achieves such damping without the VRFB power exceeding ± 2 MW (rated power of the VRFB).

Finally, the performance of the state of charge (soc) of the VRFB is shown in Fig. 6(c). It can be highlighted that, with the control system proposed, the soc does not exceed the maximum charge (overloaded state) and does not drop lower than the minimum charge (no load state).

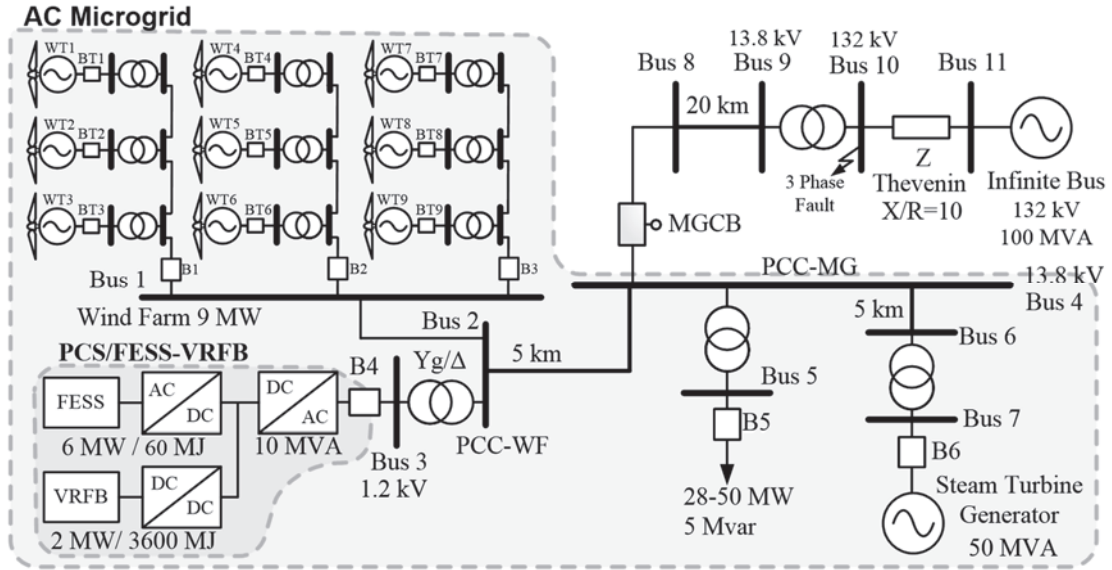


Figure 5. Diagram of the test power system with a microgrid including wind power generation and the PCS/FESS-VRFB controller. Control structure of the PCS/FESS-VRFB controller.

Source: Authors

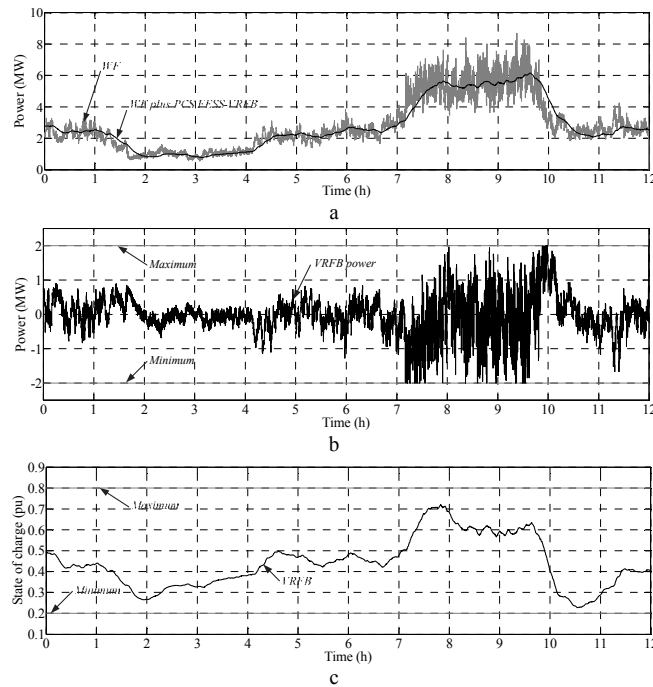


Figure 6. Results for the PCS/FESS-VRFB performance working in PL mode

a. Active power flow for the WF alone and with the PCS/FESS-VRFB controller connected

b. Active power injected by the VRFB

c. State of charge of the VRFB

Source: Authors

5.2. PCS/FESS-VRFB Performance Analysis working in FC mode

The operation of FC mode is analysed by using the same test power system of Fig. 5. To carry it out, a ground fault is

enforced at bus 10 (at $t=10.1$ s). Five cycles later, i.e. at $t=10.2$ s, with the tripping of the tie line through the opening of the breaker MGC, the fault is cleared.

For this situation, two appropriate scenarios are considered. In the first one, the MG has a high load (50 MW) and low wind for the wind farm ($P_{WG} = 1$ MW); and in the second one, the MG has a low load (28 MW) and high wind for the wind farm ($P_{WG} = 7.5$ MW). The results for each of these scenarios are shown in Figs. 7, 8, respectively.

For the test system presented in Fig. 5, before the fault, the microgrid (wind farm, steam turbine, load and the PCS/FESS-VRFB controller) imports about 14 MW from the bulk power system (for the first scenario), and exports about 14 MW to the bulk power system (for the second scenario). In this state, the frequency of the system is at 50 Hz (its rated value) in both scenarios. After the opening of the MGC breaker, the microgrid works under island conditions. In this manner, the steam turbine and the wind farm have to supply all the load; therefore, the steam turbine must automatically recover the microgrid frequency to its rated value. Figs. 7(a), 8(a) show, for both considered scenarios respectively, how the steam turbine unit can recover the frequency of the system in the base case (without the PCS/FESS-VRFB controller).

Now, the operation of the PCS/FESS-VRFB with 6 MW rated power and 60 MJ rated storage capacity for the FESS device is considered. The results of Figs. 7(a), 8(a) clearly show the working of the PCS/FESS-VRFB controller and the outstanding performance of the proposed control. After the opening of the MGC breaker, when the microgrid frequency shift surpasses the DB limits (0.15 Hz), the FC mode and the FESS device are activated. The rapid power generation/consumption of the FESS supplies the sudden imbalance occurred in the microgrid after the fault. This condition allows for a better recovery of the microgrid frequency. For the first scenario, in the case with the FESS connected, the system frequency drops to nearly 49.23 Hz

against 48.82 Hz in the base case. And for the second scenario, in the case with the FESS connected, the system frequency rises to nearly 50.64 Hz against 51.11 Hz in the base case.

The enhancement of the frequency control is achieved by the action of the PCS/FESS-VRFB controller (working the FESS device in the FC mode), which generates/consumes power for about 14.5 s. Moreover, after the frequency places within the limits of the DB value, the PL mode is activated again. This causes reductions in fluctuations of wind power and, consequently, decreases in the small frequency shifts of the microgrid.

The active power injected by the FESS for both scenarios are shown in Figs. 7(b), 8(b), respectively. It can be observed that after the opening of the MGC breaker, the FESS generates/stores its maximum power. Therefore, the wind farm with the PCS/FESS-VRFB and the proposed control assists to the recovery of the microgrid frequency. The rotational speed for the FESS (state of charge) for both scenarios is shown in Figs. 7(c), 8(c), respectively. A clear decrease/increase of the state of charge during the fault owing to the energy generation/consumption is easily observable. It can be noted in these figures that the FESS speed previous to the fault is high for the first scenario and low for the second scenario. Hence, it distinguishes a good performance of the proposed control in order to have energy to store or generate, depending on the power flow of the tie line to the utility grid. Finally, the active power injected by the synchronous generator of the steam turbine with and without the connection of the PCS/FESS-VRFB controller for both scenarios are shown in Figs. 7(d), 8(d), respectively. It is easily recognizable from these figures that with the operation of the PCS/FESS-VRFB controller the working of the synchronous generator of the steam turbine is significantly enhanced.

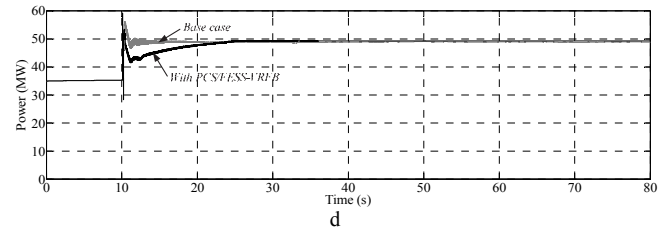
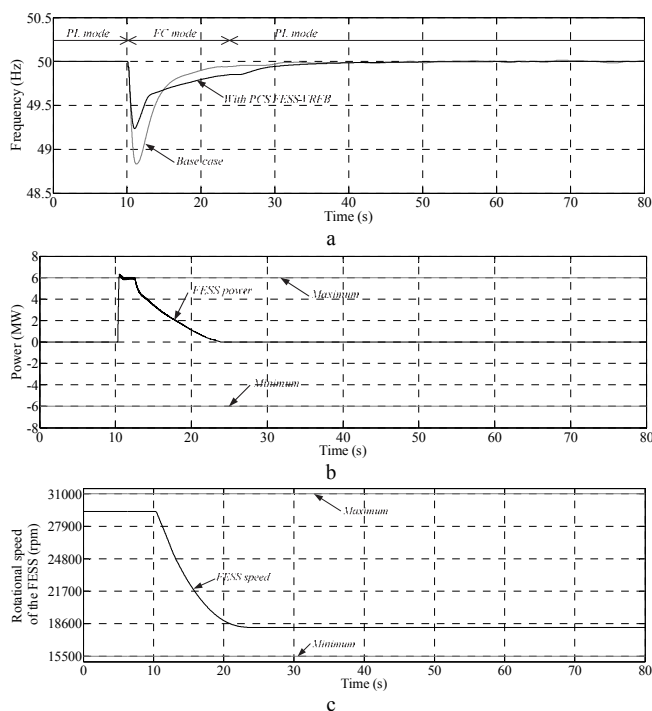


Figure 7. Results for the PCS/FESS-VRFB performance working in FC mode, first scenery (high load and low wind power)

- System frequency
 - Active power injected by the FESS
 - Rotational speed of the FESS
 - Active power of the synchronous generator of the steam turbine
- Source: Authors

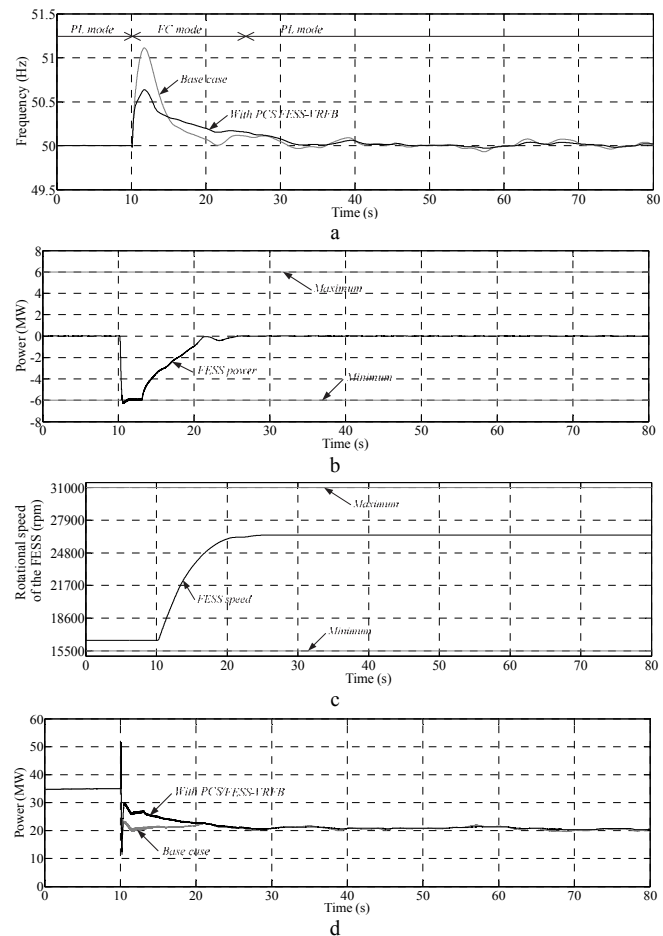


Figure 8. Results for the PCS/FESS-VRFB performance working in FC mode, second scenery (low load and high wind power)

- System frequency
 - Active power injected by the FESS
 - Rotational speed of the FESS
 - Active power of the synchronous generator of the steam turbine
- Source: Authors

6. Conclusions

This work presents control aspects of a controller composed by a power conditioning system (PCS), a Flywheel Energy Storage System (FESS) and Vanadium Redox Flow Battery (VRFB) to enhance the integration of wind power

generation into ac microgrids. A control method of the PCS/FESS-VRFB controller is proposed using two control modes, power levelling (PL) and frequency control (FC). The PL control mode uses a low-pass filter with a particular function to level the power fluctuations injected by wind generators into an electric power system. The FC control mode is employed to assist to the frequency control when significant faults occur in the system.

From the results achieved, authors concluded that the developed control methods operate satisfactorily. The PCS/FESS-VRFB controller, with the operation of the VRFB, effectively countervails the wind power fluctuations. The WF plus PCS/FESS-VRFB generates a more levelled power than that of the wind farm alone without the PCS/FESS-VRFB. Moreover, the WF plus PCS/FESS-VRFB, now with the operation of the FESS, also contributes to the recovery of the frequency when important faults take place in the system. In reference to the PL control mode, it is possible to conclude that the active power control of the VRFB using a regulator reach an outstanding handling of the stored energy, by correcting the fluctuations of wind power and avoiding the VRFB from becoming discharged or overcharged. With PL mode, the power quality of wind farms is enhanced and a suitable utilization of the energy stored for the VRFB is reached. In the FC mode, when the microgrid is isolated due to faults, causing the frequency rises or falls over a given value; the PCS/FESS-VRFB changes from PL to FC control mode conclusively, thereby activating the FESS device, and successfully contributing to recovering the microgrid frequency at its rated value. With the FC mode, excellent handling of the stored energy for the FESS is also notable, having available energy to store or generate to deal with power imbalances properly when the microgrid is isolated. In the FC mode, the wind farm with the PCS/FESS-VRFB controller provide an ancillary service to enhance the system security of the microgrid. Finally, it is clearly distinguished that optimal usage of energy storage devices is achieved with the PCS/FESS-VRFB and the control proposed. The best characteristics of the energy storage devices have been considered depending on the application. For load levelling, the VRFB is used contemplating their high discharge times, low capital cost per unit energy and high capital cost per unit power. And for frequency control, the FESS is used primarily considering their fine values of power rating, the low capital cost per unit power and high capital cost per unit energy. Hence, the incorporation of wind power generation in microgrids is efficiently enhanced with the compensation of the PCS/FESS-VRFB controller.

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A comparative study on slurry erosion behavior of HVOF sprayed coatings

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Abstract

In actual work, slurry erosion behavior of three different HVOF sprayed cermet coatings has been studied. The coatings were developed using the powders feedstock having WC fine structured sizes, Cr₃C₂-NiCr 75-25 and NiCrWSiFeB, latter conventional grain sizes. The slurry erosion testing was performed using a laboratory made pot-type slurry erosion tester, at an impact velocity of 3.61 m/s and 9.33 m/s and impact angle of 30 and 90°. The mechanism of material removal in slurry erosion was studied and discussed on microstructural investigations and mechanical properties under the erosion conditions. It was observed that the WC-CoCr cermet coating with fine WC grain exhibits higher erosion resistance as compared to conventional cermet coating due to its improved properties like low porosity, high micro-hardness and fracture toughness.

Keywords: slurry erosion; nanostructured coatings; HVOF, thermal spray coatings.

Estudio comparativo del desgaste en mezclas erosivas de recubrimientos depositados por HVOF

Resumen

Este trabajo investiga el comportamiento del desgaste en mezclas erosivas de recubrimientos depositados mediante la técnica de proyección térmica usando el proceso HVOF. Se analizaron tres tipos de recubrimientos, WC-CoCr con estructura de grano fino, Cr₃C₂-NiCr 75-25 y NiCrWSiFeB, estos últimos con tamaños de grano convencional. Los ensayos de desgaste erosivo se desarrollaron usando un tribómetro de recipiente de mezclas para evaluar la resistencia a la erosión de los recubrimientos a velocidades de impacto de 3.61 m/s y 9.33 m/s y ángulos de impacto de 30 y 90°. El mecanismo de desgaste de los recubrimientos fue estudiado y discutido sobre la base del examen microestructural y la influencia de sus propiedades mecánicas. Se observó que el recubrimiento de carburo de tungsteno exhibe mejor resistencia a la erosión comparada con los recubrimientos de carburo de cromo y metálico debido a sus propiedades de microdureza, tenacidad a la fractura y menor porosidad.

Palabras clave: desgaste en mezcla erosiva; recubrimientos nanoestructurados; HVOF; recubrimientos por proyección térmica.

1. Introduction

A common and unavoidable problem in industrial environments that constantly accompanies the operations of various mechanical components is wear that demands the development of new kind of materials with better properties for applications in those processes with severe conditions of wear, corrosive medium and exposed to high temperatures.

An alternative to solve these problems is the technique of thermal spraying which allows applying coatings of different natures, versatility and improve the properties of material surfaces, its properties and performance. This technique has gained popularity today because obtaining surfaces with exceptional properties such as: wear resistance, corrosion resistance, weight reduction and a relative low cost [1].

For industrial applications, cermets based coatings are

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widely used to modify the surface and improve the wear resistance of the mechanical components. Particularly successful and widely employed in different wear conditions are coatings WC-Co, however the feasibility of using these in certain corrosive and erosive-corrosive environments is debatable, compared with the new coatings of WC-CoCr [1,2], that create dense coatings with high hardness and good resistance to abrasion, erosion and erosion-corrosion. Slurry erosion resistance of WC-10Co-4Cr sprayed coated samples has improved by the addition nano WC-12Co powder into the coatings. However, the studies on slurry erosion of nanostructured are scarce in the literature. Based coatings CrC-NiCr systems, although usually shown lower hardness present greater stability with increasing temperature and have better corrosion resistance [3,4].

The main techniques used for the deposition are the plasma spraying air (APS) and the oxy-fuel flame at high speeds or hypersonic flame (HVOF). The HVOF technique is one of the most used method for the deposition of coatings of WC-Co and CrC-NiCr due to its unique characteristics such as high speed flow of particles to deposit and low temperature. This method causes less decomposition of WC during spraying compared to plasma spraying [5,6]. This deposition procedure has the ability to produce higher quality coatings as regards low porosity, oxide content, density and high hardness and wear resistant.

Therefore, the aims of this work is to study the behavior erosive wear of three types of coatings classified according to their grains sizes on nanostructured (WC-CoCr) and conventional and their chemical composition: coating of tungsten carbide (WC-CoCr), chromium carbide (Cr_2C_3 -NiCr 7525) and Nickel based (88HV) metal coating, all of them deposited by HVOF.

2. Materials and Experimental procedures

2.1. Coating materials

The coatings were deposited onto a steel substrate of low carbon (AISI 1020), selected due to its great industrial applicability and relatively low cost. The substrate surface was polished and blasted with aluminum oxide in order to remove impurities and obtain adequate roughness on the surface to be coated. The coating was applied achieving an average value of thickness $440 \pm 17 \mu\text{m}$ covering an area of $75 \times 25 \times 3 \text{ mm}$.

The substrates of AISI 1020 were coated through the technique called hypersonic High Velocity Oxy-Fuel / (HVOF). The commercially available feedstock materials were agglomerated and sintered with different particle sizes of the powders. One with a chemical composition related to a coating of tungsten carbide nanostructured (primary carbide size $200\text{--}500 \text{ nm}$ approximately) WC-10Co4 Cr (1350 VM / WC-731-1 / Praxair, Concord, NH, USA with agglomerated particle size of $-45 / +15 \mu\text{m}$), the other related to a chromium carbide coating of conventional structure (Cr_3C_2 -NiCr 75-25 HC Starck Amperit® 588,074, with particle size $45/15 \mu\text{m}$) and a metal compound NiCrWSiFeB coating (Colmonoy 88HV / Wall Colmonoy Corporation with particle size $05/10 \mu\text{m}$). The chemical composition of these materials is shown on Table 1.

Table 1.

Nominal composition of coatings deposited by the HVOF method.

Materials	% Wt							
	C	W	Co	Cr	B	Ni	Si	Fe
1350	5,4	Bal	10,1	4,2	-	-	-	< 0,1
7525	11,0	-	-	Bal	-	19,0	-	0,002
88HV	0,8	16,5	-	15,0	3,0	Bal	4,0	3,5

Source: Authors

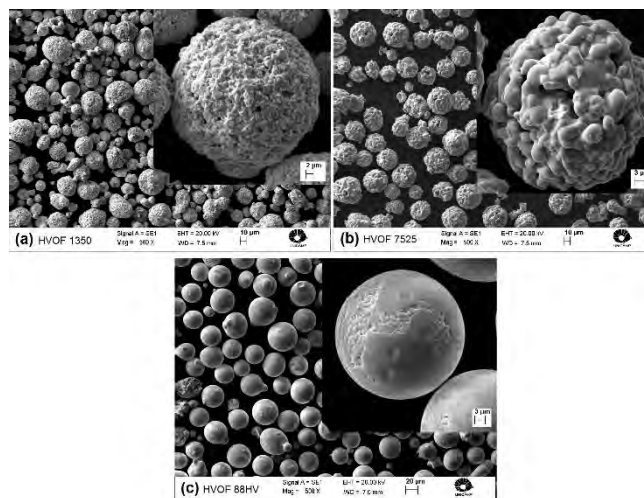


Figure 1. Images of scanning electron microscopy (SEM) micrograph of materials in powder form: (a) 1350 VM / WC-731-1, (b) Cr₃C₂-NiCr AMPERIT 75-25 and (c) Colmonoy 88HV; used as a deposit.

Source: Authors

Table 2.

Thermal spray process parameters.

Process parameters	Deposited coatings		
	1350	7525	88HV
Flow rate, O ₂ (scfh)	1850	1950	2000
Flow rate, N ₂ (scfh)	25	23	25
Flow rate (Kerosene)	6,0 GLP	5,5 GLP	6,0 GLP
Standoff distance (mm)	350÷400		

Source: Authors

Fig. 1 shows images of scanning electron microscopy micrograph of the powders used in the HVOF, the enlarged details of the images displayed agglomerated particles and sintered spherical morphology.

2.2. Thermal spray coating deposition

The technique used for thermal spraying was HPHVOF, High Pressure High Velocity Oxygen Fuel (JP- 5000, Praxair-Tafa, Concord, NH, USA). Spray application parameters used in the thermal spray process for each material were adjusted according to the recommendation of suppliers and are shown on Table 2.

2.3. Coating characterization

Coating microstructure was initially examined by both optical and scanning electron microscopy (SEM). of the top surfaces and cross-sections. Following all erosion tests the surface was examined using light and SEM to determine the

extent of degradation and to identify the material loss mechanisms.

Microhardness measurement was done with a Vickers indenter (SHIMADZU, model HMV-G). For microhardness testing, ten measurements were made on each sample in a horizontal line in the median plane of the cross section to minimize edge effects and interface with the substrate and a load of 0.3 kg was applied with a dwell time of 15 s.

Fracture toughness of the coatings was determined by indentation method at 2 kg load with 20 s dwell time. The indentations were taken at the coating cross-section and SEM images of these indentations were analyzed for studying the propagation of corner cracks and measurement of crack lengths. The fracture toughness (K_{IC}) was evaluated using well-established formulations reported by other researchers [1,7].

Porosity analysis was done using the technique of SEM microscopy and image processing. The software used was the ImageJ 1.48V and images used for analysis were selected with increased 500X.

The surface roughness (Ra) value of as-sprayed coatings was measured by an optical roughness tester (MITUTOYO SURFTTEST 211)

2.4. xperimental setup and erosion testing

The tribological properties of the coatings (erosive wear resistance) were measured using a pot type slurry erosion tribometer [1,8] (Fig. 2a). Coated samples were first ultrasonically cleaned in acetone and dried up until all the moisture was removed and weighted to 0.1 mg precision. Cleaning the samples it was also carried out after each erosive test in order to remove any of the eroded material. The specimens were disposed over the two circular plates, specially designed to evaluate particle impact angles (α) of 30 and 90° (Fig. 2b and 2c). The circular plates rotate with 660 and 1550 rpm with an instantaneous cylindrical velocity (v) of 3.61 and 9.33 m/s respectively, at the tip of specimens. SiO₂- 30/40 type (quartz sand) with grain size between 300 ÷ 425 μ m and hardness HV=1100, were used as erodent, mixed with fresh water in a concentration of 30% wt of abrasive particles (Fig. 2d). Erosion tests were performed for a maximum time of 6 hours at 1 hour intervals, in which mass loss of the samples tested, were determined to evaluate the performance of the coatings. Each test was replicated 3 times. Weight losses were measured and results are reported as the volume of material eroded per unit mass of erodent particles used during the tests. The results of mass losses were obtained by weight difference determined sample volume loss (W_v) with the following expression:

$$W_v = \frac{W_g \times 1000}{\rho} \quad (1)$$

Where W_v is the volume loss (mm³), W_g accumulated mass loss (g) and ρ the density of the deposited material (g / cm³).

The results obtained from the experiments were statistically processed in order to show their statistical significance. For data processing professional Statgraphics Centurion XV software was used. All statistical analyzes present at this work were performed with a confidence level of 95%.

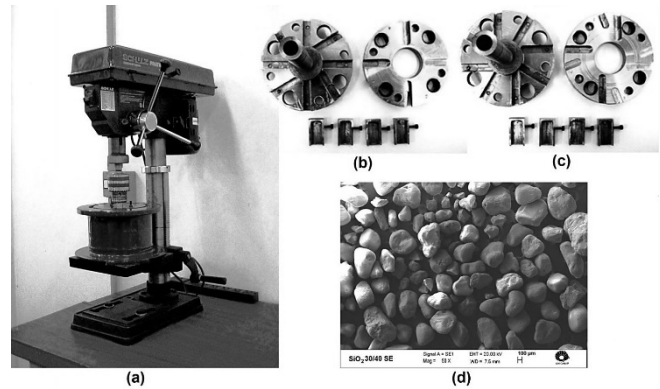


Figure 2. Experimental setup: (a) Pot type slurry erosion tribometer, (b and c) circular plates to fix samples ensuring angles impact of particles on the coatings 30 and 90°, (d) electron microscopy image of (SEM) of quartz sand (SiO₂ - 30/40 SE) used as erodent particles.

Source: Authors

Table 3.

Mechanical properties of coatings

Coatings	Mechanical properties			
	Microhardness (HV _{0.3})	Toughness (K _{IC}) MPa m ^{1/2}	Porosity (%)	Roughness (μ m)
1350	1201,6 ± 70,71	9,70 ± 1,55	0,39 ± 0,03	4,42 ± 0,32
7525	772,2 ± 66,812	7,35 ± 2,34	4,89 ± 0,69	5,51 ± 0,31
88HV	743,5 ± 21,50	6,70 ± 4,29	4,29 ± 1,50	5,97 ± 0,23

Source: Authors

3. Results and discussion

3.1. Coating characterization.

Results of microhardness, toughness, porosity and roughness of coatings are shown on Table 3.

The microhardness values of the coatings tested are very similar to those found in the literature for coatings applied by HVOF [1,9,10] process and correspond to the values provided by the manufacturer.

It is also noted on Table 3 that the coating obtained with nanostructured powder (1350), presents the lowest values of roughness and porosity and higher values of microhardness and fracture toughness if these parameters is compared to those with the rest of the coatings tested (powders with conventional size), playing a key role the dimension the particle size of the powder [1,9-12].

3.2. Microstructural examination

Fig. 3 shows the microstructures of the cross sections of coatings deposited by HVOF. According to the optical and SEM micrographs, there is good adhesion between the substrate and coatings.

SEM micrograph shown on Fig. 4a presents the microstructure of the material 1350 consisting of a dark phase related to the matrix (chrome cobalt) with a clear phase composed of reinforcing particles (WC) uniform distributed. SEM image in Fig. 4b shows the structure of the material Cr₃C₂-NiCr 75-25 AMPERIT composed of two clear phases related NiCr binder matrix and a darker linked to chromium

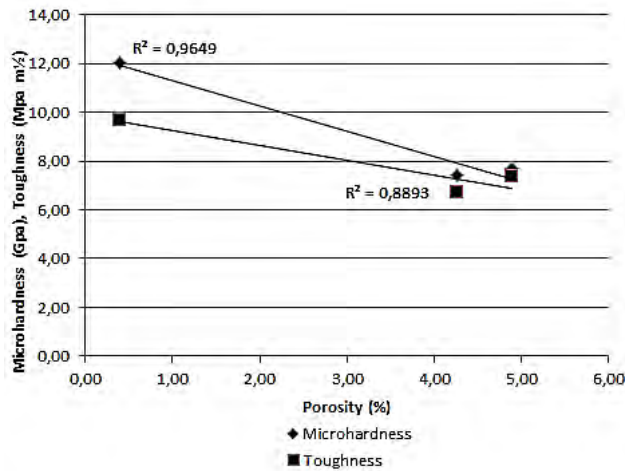


Figure 3. Relationship between porosity, micro-hardness and toughness of the materials on the analyzed deposits.

Source: Authors

carbides with a more macroscopically heterogeneous microstructure including irregular-shaped pores. Fig. 4c shows a microstructure of the 88HV coating shows a pronounced layered and heterogeneous microstructure at the macro level with regions of both phases where the WC particles may be observed in a matrix of nickel-chromium and borides of different nature, showing, moreover, a mixture of splats and incompletely melted precursor particles surrounded by irregular-shaped pores.

Images of Fig. 4 also show a more dense and homogeneous coating on tungsten carbide with more uniform particle reinforcement (WC) distribution microstructure for 1350 coating. By the other hand, SEM images are evidence of the presence of interlamellar defects such as pores and cracks, which are greater in the coatings shown in Fig. 4b and c.

3.3. Erosive wear test.

The results of the erosion experiments carried out for the different evaluated coatings are presented on Table 4 in form of erosion rate of each coating to facilitate comparison of materials with different densities. The effects of various factors influencing the results are analyzed below.

Fig. 5 shows the surface plots, where the influence of the angle and speed of impact factors of erosive particles in the dependent variable erosion rate (E_r) is observed. From the analysis of this figure it can be observed that for impact velocities of particles of 3.61 m / s the value of the angle of impact does not have a great influence on the magnitude of the rate of erosion experienced by the coatings. However, when speed is higher (9.33 m / s), the highest values of the erosion rate of the coatings are related to the impact angle of 90 °, that defines this experimental condition as the critical one and this behavior is attributed to the fragile nature of the coatings and the kinetic energy present erosive particles when the impact velocity is greater [13-15].

For the test condition of minimum speed ($V=3.61$ m / s), erosive wear behavior of the coatings can be associated to the damping effect of the solid particles with the water present in

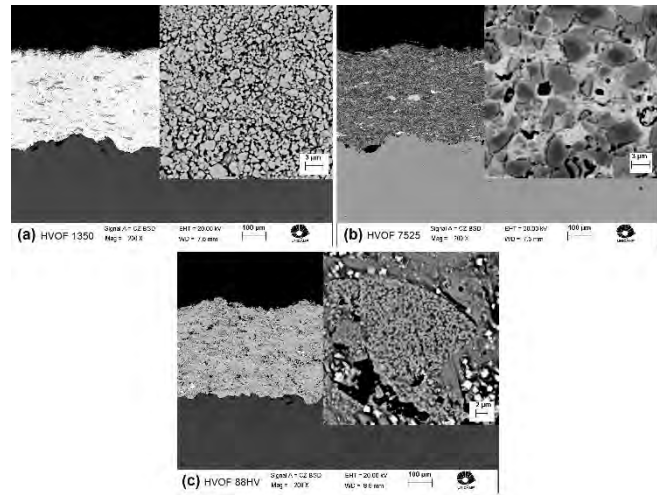


Figure 4. Images of scanning electron microscopy (SEM) of the e cross sections (a) 1350 VM / WC-731-1, (b) AMPERIT Cr3C2-NiCr 75-25 and (c) Colmonoy 88HV.

Source: Authors

Table 4.

Rate of erosive wear, E_r (mm³/Kg)

Coatings	Experimental Setup			
	$\alpha=30^\circ$	$\alpha=90^\circ$	$\alpha=30^\circ$	$\alpha=90^\circ$
	$v=3,61$ m/s	$V=3,61$ m/s	$v=9,33$ m/s	$V=9,33$ m/s
1350	2,823	2,125	8,397	9,353
7525	3,829	3,969	27,022	34,955
88HV	2,293	2,194	15,253	25,370

Source: Authors

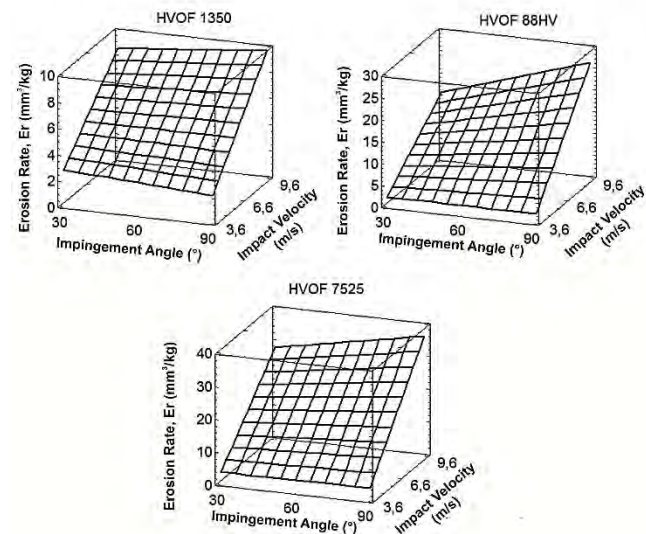


Figure 5. Erosion rates at two impingement angles and impact velocities fort each coatings.

Source: Authors

the mixture and the low kinetic energy that the solid product particles reach at this speed value [12]. When the impact velocity of the particles is increased is greater kinetic energy than those that they had and the greater energy dissipated by impacting the surface of the coatings, is used to remove the

unit volume of material eroded by the erosion mechanism [16,17]. The performance of all coatings suggests strongly that the impact speed is a parameter that has a great influence on the behavior of erosive wear coatings. Similar behaviors are reported in literature [13,18].

Fig. 6 corresponds to the analysis of variance of the mean values of erosion rate defined above experimental critical condition. From figure it can be observed that 1350 coating has the best performance in terms of erosion resistance (lower value of the erosion rate) with a great statistically significant relationship when compared to 88HV and 7525 coatings. However, these latest coatings form a homogeneous group where no statistically significant difference between them.

The higher hardness of the erodent particles is another factor that has a great influence in efficient cracks that are initiated in the target. The effect of the ratio of the target material hardness to erodent particle hardness (HV_M/HV_P) seems to be decisive for both impingement angles, but only at the critical condition of $v=9.33$ m/s. In these conditions of high kinetic energy of abrasive particles a low cycle fatigue failure of the carbide matrix and large carbide grains and microcutting occur depending on the ratio of material as well as abrasive hardness.

If material hardness exceeds that of abrasive, like 1350 coating the more wear resistant coating; the erodent particles are not able to cause plastic flow in hard target and the wear comes from a low-cycle fatigue failure of the carbide matrix and carbide grains.

If the hardness of an abrasive exceeds that of coating (88HV, 7525 NiCr) the following processes take place: penetration of abrasive into the material surface, microcutting or plowing, failure of large carbide grains, resulting in the detachment of small chips.

As was previously noted, the erosion wear resistance of the coatings depends greatly on their fragile nature, playing an important role a number of factors including the kinetic energy of particles linked to the impact velocity, the particle size, the microhardness and fracture toughness of the eroded surface [19,7,20]. In opinion of the authors, wear nature mechanism

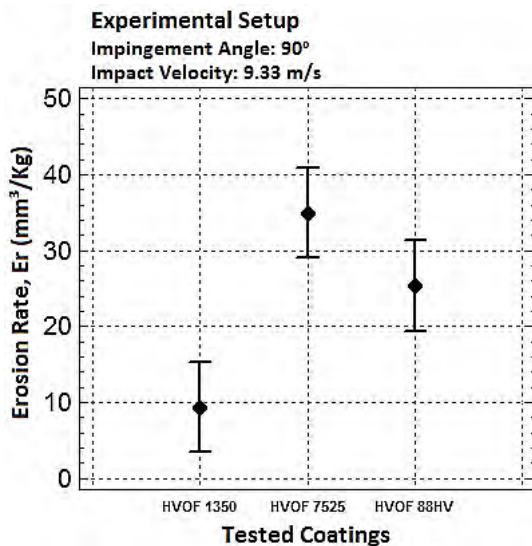


Figure 6. Analysis of variance for erosion rate under the critical condition.
 Source: Authors

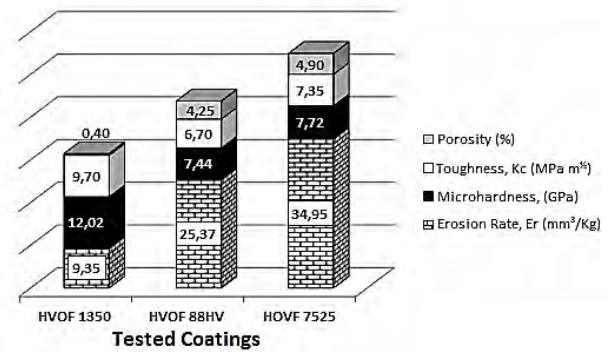


Figure 7. Erosion rate as a function of porosity level, fracture toughness and microhardness of HVOF coatings for critical condition.
 Source: Authors

ultrafine and nanometrics cermets occurs due to a complex mechanism beyond a simple classification of ductile and brittle materials, that even does not apply equally to volumetric materials and coatings, beyond the effect on each mean grain size of the carbides and density of the deposit [17,7,21].

Some of these factors mentioned above and their relation to explain the behavior of the three coatings can be seen on Fig. 7. It can be observed that the level of porosity plays an important role in erosion wear resistance. When porosity is high (greater than 2 to 3%), the wear resistance can be significantly reduced due to the low adherence of carbide grains to the binder matrix, the low hardness and toughness of these coatings and during repeated impacts of erodent particles on a given area in the coating, the stress variation let crack forming and their propagation precisely in pores as starting point [14,15,23].

From Fig. 7, it can be observed that cemented carbide coating, WC-CoCr shown the best performance for the experimental critical conditions as a result of a more dense and homogeneous coating microstructure (Fig. 3), because of its greater microhardness, lower porosity and higher fracture toughness. Nanostructured coating samples is showing a moderate type of erosion effect as shown on Fig. 7. This proves that nanostructured coating gives satisfactory performance even in extreme wear conditions due to high hardness and fracture toughness.

Although there is no model to explain satisfactorily the behavior of the coating erosion rate formed by layers deposited by the technique of thermal spraying, some researchers included in such models two variables related to the mechanical properties of the deposited material: microhardness and fracture toughness [16-18,22,23]. Fig. 8 shows the correlation obtain by the authors in order to relate properties such as fracture toughness (Kc - MPa m^{1/2}) and the microhardness of the coatings (Hv - Kg / mm²), with the erosion rate (Er). The relationship between hardness (HV) and fracture toughness (Kc) plays a dominant role in controlling erosion mechanism of the coatings. As shown in Fig. 8, 1350 coating gives satisfactory performance even in extreme wear conditions due to high hardness and fracture toughness ensuring the lowest levels of erosive wear. Hardness and toughness of the coatings can be improved by

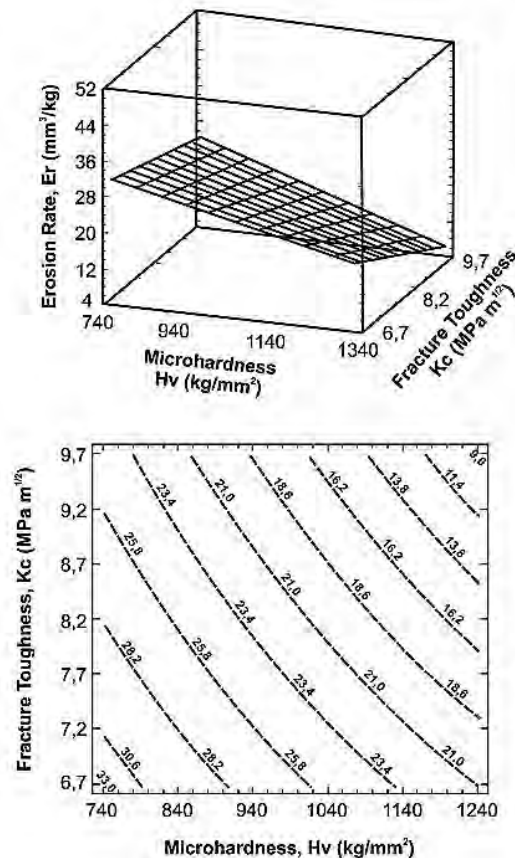


Figure 8. Correlation between erosion rate and microhardness as well as fracture toughness for analyzed coatings (a) Surface plot. (b) Contour plot
Source: Authors

decreasing the WC grain size to near nanometer range that results in enhanced erosion resistance.

The behavior of this nanostructured coating suggests that it may be possible to increase the hardness and wear resistance of these materials still further without compromising toughness substantially.

Important decisions can be made from the behavior of wear rate of the tested coatings from the aforementioned relationship between hardness and toughness of the material, aspects very controversial because generally increased hardness means a substantial decrease in fracture toughness. Fig. 8 presents the relative ranking of the coatings investigated with respect to erosion rate and could be explained in opinion of authors of the present study, by their different fracture toughness values whereas the hardness seems to be of minor importance.

As shown in the above figure, greater wear resistance coating corresponds to higher microhardness and fracture toughness (nanostructured). Such behavior suggests a major role of fracture toughness more than the microhardness of the material.

However in the analysis of the figure the role related to relationship between hardness of the abrasive particle and target must be considered. Figure for example can be seen that hardness below 1100 HV, the wear of materials increases drastically. Beyond and with the highest fracture toughness

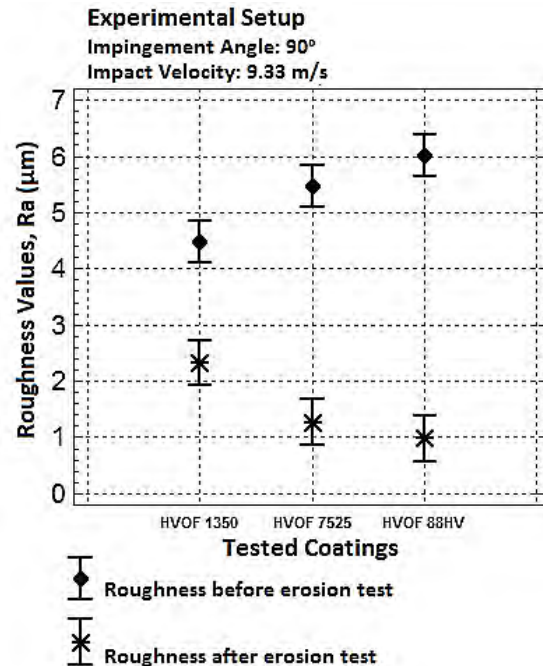


Figure 9. Variance analysis of mean values of the roughness of coatings before and after erosion test.
Source: Authors

values, greater resistance to wear is achieved by tested materials (Fig. 8a).

Fig. 8b shows a contour plot that illustrates the best combination to obtain a significant wear resistance by achieving a hardness between 1170-1240 HV and a fracture toughness, $k_c = 9-9.7 \text{ MPa m}^{1/2}$.

Another factor used in the characterization of surface coatings was roughness. Determined before and after erosion tests (initial roughness values of the coatings shown on Table 3) the values obtained after eroding surfaces with a statistical analysis of variance can be observed on Fig. 9.

Fig. 9 shows clearly two homogeneous groups, one formed by coating tungsten carbide (1350) and another by the chromium carbide coating and the metallic coating (7525 and 88HV). Between the two groups there is a statistically significant difference of the roughness values, and that behavior is similar before and after being abraded surfaces. However, the average values of the roughness of the coatings 88HV and 7525 have no statistically significant difference between them. Compared individually roughness values of the coatings, shows that there is a statistically significant difference between mean values of initial roughness and erosion of the eroded surfaces. A rough surface is more susceptible to erosion than a smooth surface. The surface roughness can also influence on the flow near the surface. The coating surface may also contain more binder than the rest of the material, especially after sintering. The binder is softer and easier to erode than the carbide particles. In as sprayed specimens with lower surface roughness the width and depth of the grooves were much smaller as compared to the grooves in those with higher surface roughness condition suggesting lower penetration in nanostructured coatings with high hardness.

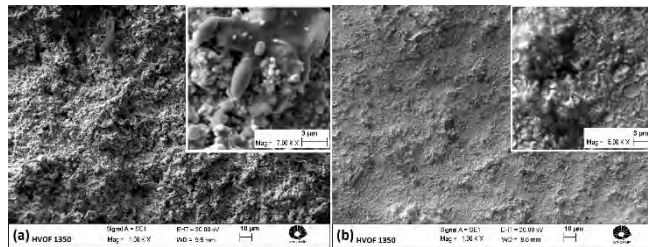


Figure 10. Images of scanning electron microscopy (SEM) of the original (a) and eroded surfaces (b) coating nanostructured 1350 VM / WC-731-1 in critical condition.

Source: Authors

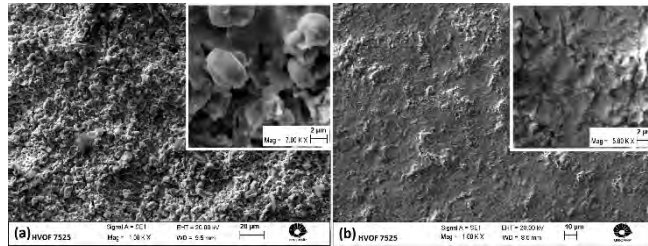


Figure 11. Images of scanning electron microscopy (SEM), (a) Original surface (a), (b) eroded surfaces of the conventional coating Cr3C2-NiCr 75-25 AMPERIT in critical condition.

Source: Authors

Images of scanning electron microscopy on Figs. 10 and 11 present at the critical conditions ($V=9.33$ m/s, $\alpha=90^\circ$) the surface coating of tungsten carbide (1350) and chromium carbide (7525) which showed the best and worst performance respectively. It can be seen clearly the variation of surface roughness before and after erosion. The analysis concluded that the decrease of the surface roughness in the coating tungsten carbide was 45.48% and a in the case of chromium carbide coating of 77.5%, being a factor in this behavior the value of microhardness of the coatings surfaces, which when greater causes less loss of roughness [14,15,25].

High magnification images of Figs. 10 and 11 details defects and damage shown on the surfaces of the coatings caused by erosion as: fractured zones, formation of multiple cracks, individual carbide particle removal exposing the soft metallic binder for erodent particles impacts creating the voids at their original sites where these carbides were, broken carbides grains, craters, etc.

Figures show that the mechanism of material removal in both coatings was due to the appearance of microcracks and caused by the repetitive impact of solid particles in a given region cracks, which propagate and cause the extrusion of the carbides reinforcement of the binder matrix, characteristic mechanism of brittle materials. In literature related to this topic similar behaviors can be found [1,10].

In coatings with conventional grain sizes it was observed that the increase rate of erosion is associated with lower hardness and lower fracture toughness. In the above figure shows a higher degree of plastic deformation as under its lower fracture toughness develop and grow cracks in its wake cause the extrusion of carbides grains, exposing the soft phase matrix with the repetitive impact of the erosive particles increases wear. Evidence was found from wear scar that some erosion damage can be localized at large pores, or isolated porous areas in 88HV

and 7525 NiCr coatings. As a consequence to repetitive high energetic impacts of erodent particles, cracking occurs over the coated surface, and with the course of time, these cracks have been grown up and propagated into radial and lateral cracks. At the junction of these radial and lateral cracks WC grain get loosened and came out of the surface leaving a visible void or pit as shown on Fig. 11.

Meanwhile the material made from nanostructured powders has a less consistent plastic deformation and coating erosion took place from few sites and it is mainly due to the chipping of WC grain and ploughing of soft metallic binder. The coating surface is not heavily eroded, some shallow pits are clearly visible and minor pullout of WC grain confirms the better erosion resistance. Nanostructured coating possess higher fracture toughness value, which had suppressed the nucleation and propagation of cracks formed by repeated impacts of erodent particles. Fig. 10 shows the crack propagation restriction near fine WC grains and which may have taken place to high fracture toughness offered by nanostructured phase. Due to high fracture toughness and hardness value the cracking followed by the pullout of WC grain is suppressed in nanostructured coating.

3. Conclusions

1. The samples coated with nanostructured powders (1350 VM / WC-731-1) had the highest microhardness value, lower porosity, higher fracture toughness and lower roughness, playing a key role in a low erosion wear. All these improvements are related with size powder particles, the density of the coating and the more uniform reinforcement carbides (WC) distribution.
2. The speed and angle of impingement of the solid particles in the mixture influences the behavior of the wear resistance, this can be attributed to the fact that with increasing speed of the particles, have more kinetic energy causing further damage on the coating surface in correspondence with the relative material hardness and erosive particle. Thus the experimental condition of greater value speed (9.33 m / s) and impact angle of 90° was defined as the most critical, where all coatings experienced the greatest value of the ratio of erosive wear, more AMPERIT incidence coatings Cr3C2-NiCr 75-25 and Colmonoy 88HV.
3. With the analysis of scanning electron microscopy of the coating surfaces was observed that the mechanism of material removal in the coatings was caused by fatigue of the product of repetitive impacts of the solid particles surface at a given site, causing the formation of microcracks, cracks and the spread of these. These processes promote loss of adhesion of carbide reinforcements to the binder matrix and extrusion of them, favoring the coating higher ratio of microhardness of the deposit with respect to the hardness of the abrasive, greater fracture toughness, denser structure and less porosity.

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Implementation of risk management to equipment and productive systems

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Abstract

This paper aims to establish a methodology for risk analysis of equipment and production systems, and identify those assets subject to the validation process. It provides a set of instructions that describing in detail the steps to perform a validation schedule with bases residual risk. The study was conducted at the National Center for Scientific Research of Cuba, production department. The work is based on the implementation of the IEC 60812 standard, analysis of failure modes, effects and criticality (FMEA). In partnership with this standard it was used other documents necessary for application as the series of standards IEC 60300-3-1 and IEC 61025. Among the main results was obtained the risk map of the company and were implemented control actions once identified residual risk. These results allow to establish the minimum period necessary for validation of technological systems of the company.

Keywords: methodology; risk; residual risk; validation.

Aplicación de la gestión de riesgo a equipos y sistemas productivos

Resumen

El presente trabajo tiene como objetivo establecer una metodología para el análisis de riesgo de equipos y sistemas productivos, así como identificar aquellos activos sujetos al proceso de validación. Se proporciona un conjunto de instrucciones que describen detalladamente los pasos a seguir para realizar el cronograma de validación con bases al riesgo residual. El estudio se realizó en el Centro Nacional de Investigaciones Científicas de Cuba, dirección de producción. El trabajo se basa en la implementación de la norma IEC 60812, análisis de los modos de fallo, efectos y criticidad (AMFEC). De conjunto con esta norma se utilizarán otros documentos indispensables para su aplicación como son la serie de normas IEC 60300-3-1 e IEC 61025. Entre los principales resultados se obtuvo el mapa de riesgo de la empresa y las acciones de control implementadas una vez identificado el riesgo residual. Estos resultados permitieron establecer el período mínimo indispensable para la validación de los sistemas tecnológicos de la empresa.

Palabras clave: metodología; riesgo; riesgo residual; validación.

1. Introducción

Los establecimientos que manejan sustancias peligrosas poseen, en general, elevados niveles de seguridad; sin embargo, la gravedad de los accidentes que pueden producirse en sus instalaciones, unida a la gran repercusión social y a la incertidumbre que generan, viene motivando que exista por parte de las autoridades competentes y del sector industrial una gran sensibilidad y manifiesta preocupación orientada a reducir los riesgos potenciales de estas actividades. Esto conduce a generar líneas de actuación y

mecanismos que faciliten el desarrollo e implantación de medidas legales, técnicas, instrumentales, etc., que refuercen tanto las acciones preventivas como las dirigidas a mitigar las consecuencias de los accidentes [1,2].

A pesar de que la terminología relativa al análisis del riesgo se utiliza a menudo con escaso rigor, existe un elevado nivel de aceptación de los conceptos involucrados en los términos que se citan a continuación. En un contexto general “riesgo” se define como la probabilidad de ocurrencia de un evento adverso determinado sobre la salud humana, los bienes materiales o el medio ambiente, como consecuencia

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de la exposición a un “peligro” (ciertos productos químicos, tecnologías, fenómenos naturales, etc.) que puede materializarse a través de un suceso accidental. Se entiende por “análisis del riesgo” el uso de la información disponible para identificar los peligros existentes y estimar el nivel de riesgo presente. Por “evaluación de riesgos” se entiende el proceso por el cual se juzga la aceptabilidad del riesgo estimado. Finalmente, la “gestión de riesgos” es el proceso de decidir qué debería hacerse respecto a un peligro, a la población expuesta o a los efectos adversos, implantando la decisión y evaluando sus resultados [3,4].

Los métodos para la identificación de riesgos suelen estar basados en los principios de diseño, listados de verificación, buenas prácticas, experiencia y sentido común [5]. Sin embargo, no siempre brindan un grado de exploración suficientemente comprensivo de los escenarios donde existe la potencialidad para la ocurrencia de fallas.

Las técnicas de Identificación o Análisis de Riesgos pueden clasificarse a grandes rasgos de la siguiente manera:

- ✓ **Métodos Comparativos:** se basan principalmente en el conocimiento adquirido en base a la experiencia. Las listas de verificación (*checklists*), el análisis histórico de accidentes, y los índices de riesgos son métodos comparativos [6].
- ✓ **Métodos Fundamentales:** son formas estructuradas que ayudan a estimular a un grupo de personas a aplicar la previsión en conjunción con su conocimiento de las tareas, mediante la formulación de ciertas preguntas o el uso de palabras guía. Entre los ejemplos de este tipo de metodología se pueden citar los siguientes:
 - HAZOP (*Hazard and Operability Studies*) Estudios de Riesgo y Operatividad [7-10].
 - FMEA (*Failure Modes and Effects Analysis*) Análisis de Modos de Falla y Efectos [11-13].
 - Análisis de las Tareas [14].
 - Análisis “*What-If*” [15].
 - PHA (*Preliminary Hazard Analysis*) Análisis Preliminar de Riesgos
- ✓ Diagramas Lógicos de Falla: son métodos que mediante gráficos representan la lógica de una falla (por ejemplo, Árboles de Falla y de Eventos) [16].

Virtualmente cualquier operación industrial en la que se utilice energía, maquinarias, productos químicos, etc., es potencialmente riesgosa, y los accidentes en el ámbito laboral, tales como caídas, electrocución, contacto con partes de equipos, etc., son comunes a la mayoría de las industrias.

El presente trabajo tiene como objetivo principal establecer una metodología para el análisis de riesgo de equipos y sistemas productivos, así como identificar aquellos activos sujetos al proceso de validación.

El proceso de validación se puede definir como la técnica mediante la cual se establece evidencia documentada, con alto grado de aseguramiento, de que un proceso específico proporciona en forma consistente un producto que cubre con las especificaciones predeterminadas y sus atributos de calidad [17-19].

Las Buenas Prácticas de Fabricación (BPF) exigen que los fabricantes identifiquen las tareas de validación que son necesarias para demostrar el control de los aspectos críticos de sus operaciones específicas [20]. Un paso fundamental en

la toma de decisiones sobre cuál o cuáles son los equipos o sistemas que serán sometidos al proceso de validación es una tarea compleja en cualquier proceso, que generalmente se inicia con un análisis de criticidad.

El Análisis de Criticidad es una técnica que permite establecer la jerarquía o prioridades de procesos, sistemas y equipos, creando una estructura que facilita la toma de decisiones acertadas y efectivas, direccionando el esfuerzo y los recursos en áreas donde sea más importante y/o necesario [21,22]. En el caso bajo estudio el análisis de criticidad se obtendrá de una evaluación inicial de los riesgos presente en el proceso.

2. Materiales y métodos

Para el análisis de riesgo de los equipos y sistemas se utilizará la norma **IEC 60812: 2006** elaborada por el comité técnico 56 de IEC: Confiabilidad, de acuerdo con las directivas ISO/IEC, parte 2. Esta norma internacional describe el análisis de los modos de fallo y sus efectos (AMFE) y al análisis de los modos de fallo, de sus efectos y criticidad (AMFEC) y proporciona una guía sobre cómo aplicarlos [23].

Todas las consideraciones cualitativas generales presentadas para el AMFE se aplicarán al AMFEC, puesto que este último es una extensión del anterior.

De conjunto con la norma **IEC 60812: 2006**, se utilizarán otros documentos indispensables para la aplicación de esta norma. Estas series de normas se utilizarán indistintamente para la supervisión y control del riesgo residual.

Tabla 1.
Cuantificación de valores para determinar el impacto de equipos y sistemas productivos.

Valor	Descripción	Definición
1	Imperceptible	Ningún efecto en el producto o en los procesos subsecuentes.
2	Muy menor	En el proceso muy probablemente no se observará la falla. Falla no vital.
3	Menor	Proceso ligeramente afectado. Falla no vital la mayoría de las veces.
4	Muy bajo	El proceso es afectado. Falla que no necesita reparación inmediata. Falla no vital observada frecuentemente.
5	Bajo	En el proceso se observará la falla, producto con afectaciones no vitales. La falla en la parte no vital requiere reparación inmediata.
6	Moderado	El desempeño del Proceso/Producto degradado, el sistema opera parcialmente de forma segura. Partes y piezas inoperables.
7	Severo	Efecto potencial peligroso. Falla dependiente en el tiempo. Subsistema inoperable.
8	Muy severo	Efecto principal en el proceso, re-procesos y reparaciones. Desempeño del proceso afectado severamente. Rompimiento de las operaciones del proceso siguiente.
9	Peligroso	Efecto extremo en el proceso, sistema dañado e inoperable, capaz de parar el proceso sin accidente. Pérdidas involuntarias del producto.
10	Muy peligroso	Pérdida total de producto. Seguridad comprometida, falla repentina muy Riesgos.

Fuente: El autor.

- ✓ IEC 60300-3-1:2003. Gestión de la confiabilidad. Parte 3-1: Guía de aplicación. Técnicas de análisis de la confiabilidad. Guía metodológica [24].
- ✓ IEC 61025: 2006. Análisis de árbol de fallos (AAF) [16].

2.1. Procedimiento para determinar la severidad o criticidad del sistema

Se trata de la asignación de valor a la falla en función del impacto que ocasiona al sistema, al ambiente, a la producción, a la seguridad de los operadores. Se basa en criterios previamente definidos por normas o criterios definidos por autoridades regulatorias, Ver Tabla 1.

Tabla 2.
Cuantificación de la frecuencia de fallos en equipos y sistemas productivos.

Valor	Ocurrencia	Definición	Probabilidad
1	Remota	Falla improbable. No existen fallas asociadas con este proceso o con un producto casi idéntico.	1 en 150 000
2	Muy poca	Solo fallas aisladas asociadas con este proceso o con un producto casi idéntico.	1 en 30 000
3	Poca	Fallas aisladas asociadas con este proceso.	1 en 1 500
4	Moderada	Este proceso o uno similar ha tenido fallas ocasionales.	1 en 450
5			1 en 200
6			1 en 100
7	Alta	Este proceso o uno similar ha fallado a menudo.	1 en 50
8			1 en 15
9	Muy alta	La falla es casi inevitable.	1 en 6
10			>1 en 3

Fuente: El autor.

Tabla 3.
Cuantificación de valores para detectar la desviación no deseada en equipos y sistemas productivos.

Valor	Descripción	Definición
1	Con seguridad	Los controles detectarán la existencia del defecto antes de que el producto pase a la siguiente operación. Es importante el control de las materias primas de acuerdo a las especificaciones de la organización.
2	Muy Alta	Los controles tienen una buena oportunidad de detectar la existencia de la falla antes de que el proceso de manufactura haya sido completado (monitoreo con pruebas en operaciones intermedias).
3	Alta	
4	Moderada-Alta	
5	Moderado	Los controles probablemente encuentren la existencia de la falla, pero no se puede aceptar hasta que las pruebas hayan sido completadas (monitoreo con pruebas en proceso).
6	Bajo	
7	Muy bajo	Los controles pueden detectar la existencia del defecto, pero la detección no ocurre hasta que se haya procesado el lote final.
8	Remoto	
9	Muy remoto	Detección muy baja, los controles de la organización probablemente no detecten la existencia del defecto, pero este puede ser detectado por el cliente.
10	Indetectable	Seguridad absoluta de no detección, los controles no podrán detectar la existencia del defecto.

Fuente: El autor.

2.2. Procedimiento para determinar la ocurrencia o frecuencia de la falla

Es el valor asignado a la falla en función de que tan frecuente el modo de la falla ocurre como resultado de una causa específica. El número de clasificación de ocurrencia se representa en una tabla y en la medida de lo posible se basa en la frecuencia real de ocurrencia. Ver Tabla 2.

2.3. Procedimiento para determinar la detección de la falla

Permite medir qué tan efectivo es el control para detectar y corregir la desviación no deseada en el sistema o equipo. Un valor muy elevado significa que no se está haciendo un control adecuado de los síntomas de la falla. Ver Tabla 3.

2.4. Procedimiento para determinar el Número de Prioridad de Riesgo (NPR)

El NPR indica la prioridad con que se deben seleccionar las actividades para prevenir las ocurrencias de fallas que ocasionan los efectos.

$$NPR = S \times O \times D \quad (1)$$

2.5. Criterios de aceptación del riesgo

Según los valores asignados de **Severidad, Ocurrencia y Detección** de la falla, el valor de riesgo cuantitativo se encuentra en un intervalo de 0-1000. En la Tabla 4, se define el intervalo de clasificación del riesgo.

2.6. Medidas para la supervisión y control del riesgo residual

- ✓ Se incluirá en el cronograma de validación aquellos equipos que consten de 2 o más elementos cuyo Número de Prioridad de Riesgo Residual (NPRR) sea alto, moderado-alto o moderado-bajo (Equipos Crítico),
- ✓ Se calificarán aquellos sistemas o elementos cuyo Número de Prioridad de Riesgo Residual (NPRR) sea alto o moderado-alto (Equipos Semi-Crítico),
- ✓ Se implementarán procedimientos de mantenimiento preventivo a los equipos y sistemas cuyo Número de Prioridad de Riesgo Residual (NPRR) sea moderado-bajo (Equipos Semi-Crítico),
- ✓ Se asistirán de forma correctiva a los equipos, elementos y sistemas cuyo Número de Prioridad de Riesgo Residual (NPRR) sea bajo (Equipos No Crítico),
- ✓ Se listarán en el formato que se muestra a continuación aquellos equipos, elementos o sistemas propuestos a validación/calificación. Ver Tabla 5.

Tabla 4.
Intervalo de clasificación del riesgo.

Valor cuantitativo	Clasificación	Criticidad
500 – 1000	Alto	Crítico
300-499	Moderado-Alto	
120-299	Moderado-Bajo	Semi-Crítico
1-119	Bajo	No crítico
0	Sin Riesgo	

Fuente: El autor.

Tabla 5.

Aplicación de la gestión de riesgo en el área de saponificación.

Nombre del proceso: Saponificación			Fecha de elaboración: 25 de junio de 2016						Empresa: CNIC				
Responsable: Michael Herrera Galán			Fecha de revisión: 5 de julio de 2016						Dirección. Producción				
Equipo/Sistema: Reactores (saponificador)													
Elemento	Función	Modo de Falla	Efecto de Falla	Severidad	Causa de Falla	Ocurrencia	Controles actuales	Detección NPR	Acción recomendada	Resultados de acciones			
										Severidad	Ocurrencia	Detección	NPRR
Depósito cilíndrico vertical	Almacenar la reacción durante la operación de saponificación	Depósito averiado con pases de vapor	No se puede efectuar la reacción	8	Presencia de grietas, camiseta pochada	2	PPO de operación del tanque saponificador	2 32	Los controles actuales son suficientes	8	2	2	32
Motor del tanque saponificador	Transformar energía eléctrica en mecánica para el accionamiento del agitador	Motor no gira	No hay energía mecánica para el accionamiento de las paletas	7	Perdida de aislamiento, quema del enrollado, falta de la tensión de alimentación	5	PPO de mantenimiento o preventivo	3 105	Supervisión del AT-3	7	4	2	56
Reductor del tanque saponificador	Disminuir la velocidad de rotación del motor	Reductor sin aceite	El motor gira a velocidad descontrolada	6	Presencia de grietas, salideros	4	PPO de mantenimiento o preventivo	3 72	Los controles actuales son suficientes	6	4	3	72
Agitador del tanque saponificador	Homogenización, de la cera utilizada con el KOH	Hélices deformadas Hélices desacopladas al motor	No ocurre la disolución de KOH	9	Golpes, falso acoplamiento	2	-	2 36	Inspección visual	9	2	2	36
Variador del tanque saponificador	Controlar la velocidad de rotación del motor	Fallo en la tensión	Movimiento de las hélices del agitador descontrolado	7	Fallo en sistema de energía eléctrica	2	PPO de mantenimiento o preventivo	1 14	Los controles actuales son suficientes	7	2	1	14
		Fallo en el programa		7	Calibración incorrecta	5	PPO de mantenimiento o preventivo	8 280	Calificación	7	3	6	126
		Fallo en el potenciómetro		7	Mala operación	7	PPO de mantenimiento o preventivo	4 196	Disminuir frecuencia de intervención	7	4	4	112
Indicadores de medición	Indicar los parámetros de control	Falsa indicación	Reacción química fuera de parámetros	6	Calibración incorrecta, montaje incorrecto.	6	PPO de calibración de los instrumentos de medición	6 216	Control del plan de calibración	6	4	6	144

Fuente: El autor.

Tabla 6.

Plantilla resumen para listar las acciones tomadas una vez identificado el riesgo residual asociado.

Proceso: Elemento	Modo de falla	Acciones	NPR	NPRR

Fuente: El autor.

2.6. Frecuencia de validación

El tiempo máximo establecido para la validación dependerá del análisis de riesgo y por consiguiente de la

crítica de los equipos y sistemas en el proceso

3. Resultados

El primer resultado está dirigido a identificar los equipos y sistemas en cada área productiva. Se describe su función principal, modo, efectos, causa de la falla potencial, los controles asociados a los activos; así como el número de prioridad de riesgo (NPR) y el número de prioridad de riesgo residual (NPRR). En la Tabla 6, se muestra el resultado del análisis en el área de saponificación (reacción química). Es válido destacar que el procedimiento planteado es el mismo para todos los

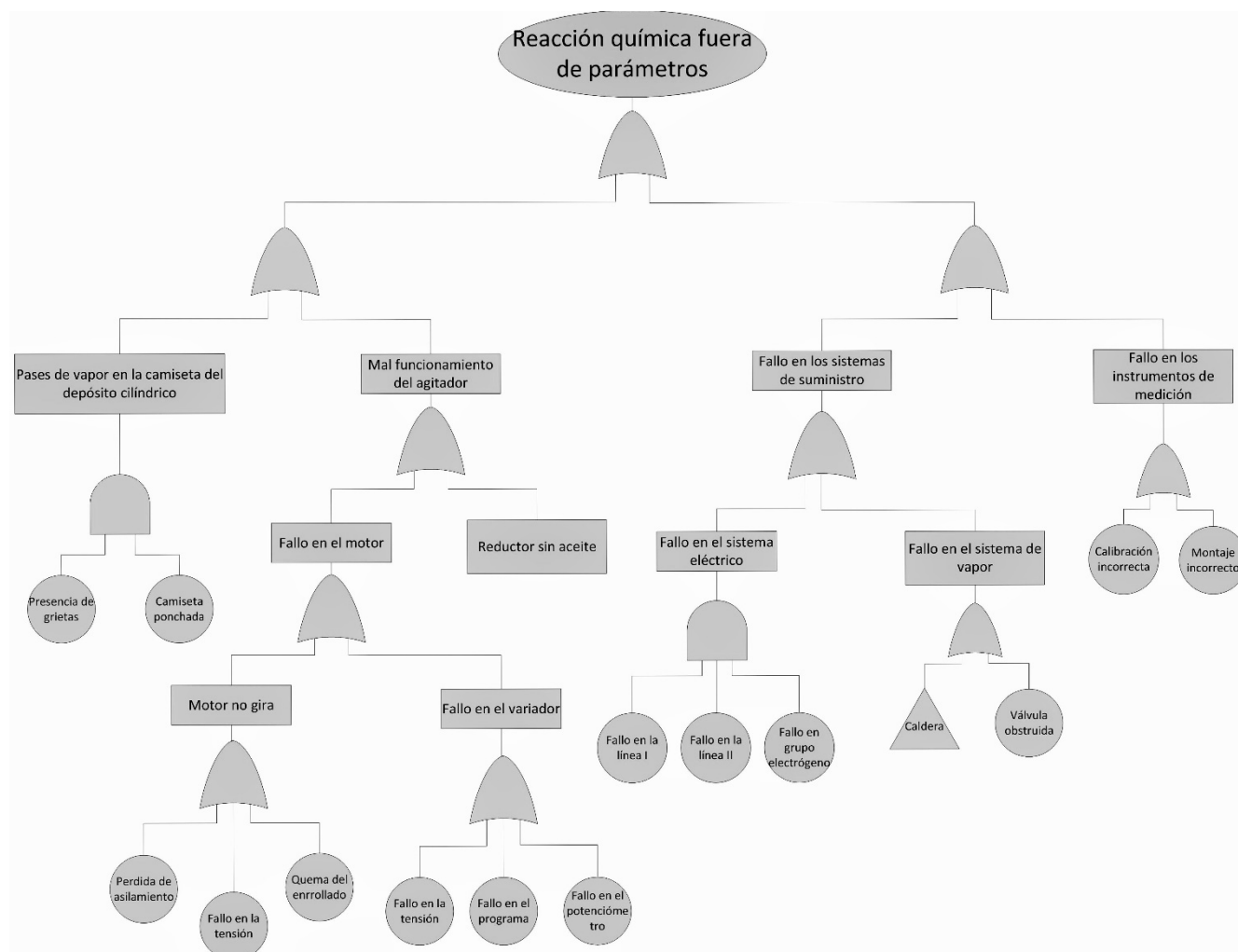


Figura 1. Resultado del árbol de fallas en el tanque saponificador.
Fuente: El autor.

activos de la empresa. A modo resumen solo se ilustra el resultado en un tipo de activo (los reactores químicos).

Posteriormente se obtuvo el árbol de falla de cada activo cuyo número de prioridad de riesgo residual es superior a 120; o sea equipos de alto y moderado riesgo. El AAF es una herramienta importante en la investigación de problemas y riesgos potenciales ya que proporciona información para mejorar, modificar y optimizar a los equipos y sistemas. A continuación se ilustra el AAF para el activo antes mencionado.

Una vez concluida las dos etapas anteriores se confeccionó el mapa de riesgo de la empresa. A continuación, se muestra en forma de radial los equipos y sistemas, críticos y semi-críticos de la empresa.

Finalmente se confeccionó la Tabla 7 que resume las acciones tomadas una vez identificado el riesgo residual asociado y aplicadas las acciones de control.

4. Discusión

La Tabla 1 muestra el resultado del AMFEC en el área de saponificación. El objetivo de este proceso es transformar los ésteres carboxílicos, presentes en la cera refinada de caña, en alcoholes de alto peso molecular y en sales de ácidos, lo que se logra mediante una reacción química. La saponificación se realiza en el área número 1 de la planta de producción, la cual está estructurada en dos niveles con los siguientes equipos y sistemas.

En el nivel 2 están ubicados el tanque dosificador, el reactor químico (Saponificador), el variador de frecuencia, ventiladores axiales y los extractores centrífugos. En el nivel 1 está ubicados el escamador, los controles de temperatura, la bomba de KOH, la bomba de retorno de condensado, el disolutor y el tanque de recuperación de condensado. Ambos niveles son serviciados por los sistemas de distribución de agua, energía eléctrica, vapor y ventilación. Ver Fig. 3 para una mejor comprensión del proceso

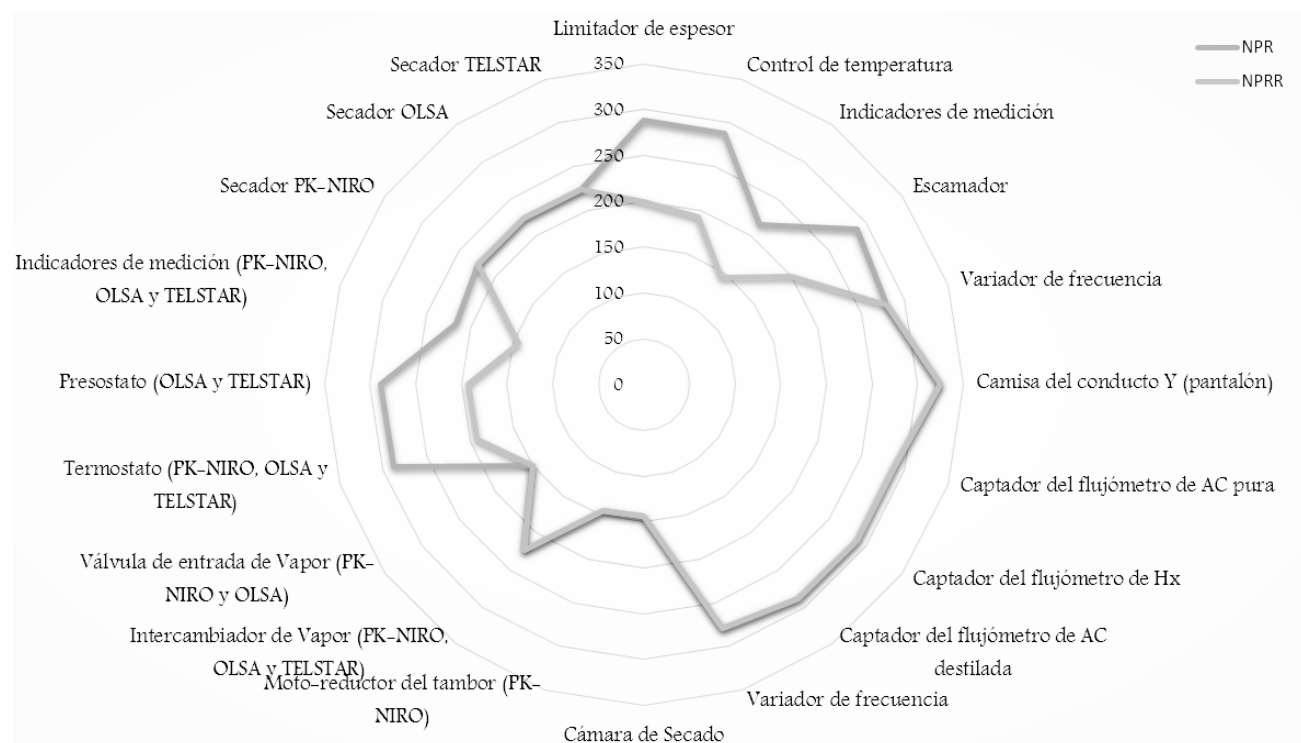


Figura 2. Mapa de riesgo de la empresa.
Fuente: El autor.

Tabla 7.
Resumen de acciones una vez identificado el riesgo residual asociado

Proceso: Saponificación, Extracción, Purificación, Secado y Destilación				
Elemento	Modo de falla	Acciones tomadas	NPR	NPRR
Limitador de espesor	Pérdida de fijación	Modificar/Crear PPO	288	200
Control de temperatura del escamador	Falsa indicación	Modificar/Crear PPO	288	192
Variador del tanque saponificador	Fallo en el programa, Fallo en el potenciómetro	Modificar/Crear PPO	280	126
Captador del flujómetro de AC pura	Contar la cantidad de litros establecidas en el flujómetro	Modificar/Crear PPO	288	288
Captador del flujómetro de AC destilada	Contar la cantidad de litros establecidas en el flujómetro	Modificar/Crear PPO	288	288
Captador del flujómetro de Hx	Contar la cantidad de litros establecidas en el flujómetro	Modificar/Crear PPO	288	288
Variador de frecuencia de las centrífugas	Controlar la velocidad de rotación del motor	Modificar/Crear PPO	280	280
Cámara de Secado	Contaminación del producto	Modificar/Crear PPO	144	144
Moto-reductor del tambor (PK-NIRO)	Tambor no gira o gira a velocidad descontrolada	Modificar/Crear PPO	144	144
Intercambiador de Vapor (PK-NIRO, OLSA y TELSTAR)	Disminución de la temperatura de trabajo en la cámara de sacado	Modificar/Crear PPO	224	224
Válvula de entrada de Vapor (PK-NIRO y OLSA)	Válvula no acciona	Modificar/Crear PPO	150	150
Termostato (PK-NIRO, OLSA y TELSTAR)	Inadecuada temperatura de trabajo en la cámara de secado.	Modificar/Crear PPO	288	192
Presostato (OLSA y TELSTAR)	Inadecuada presión de vacío en la cámara de secado.	Modificar/Crear PPO	288	192
Indicadores de medición (PK-NIRO, OLSA, TELSTAR, Saponificador)	Producto intermedio fuera de parámetros	Modificar/Crear PPO	216	144
Camisa del conducto Y pantalón	Pérdida de calor	Calificar	324	324
Escamador	Fallo en el limitador de espesor, fallo en el control de temperatura y fallo en los instrumentos de medición	Validar	288	200
Secador PK-NIRO	Fallo en la cámara de secado, en el moto-reductor del tambor, en el intercambiador y válvula de vapor, en el termostato y en los instrumentos de medición	Validar	224	224
Secador OLSA	Fallo en la cámara de secado, en el intercambiador y válvula de vapor, en el termostato, en el presostato y en los instrumentos de medición	Validar	224	224
Secador TELSTAR	Fallo en la cámara de secado, en el intercambiador y válvula de vapor, en el termostato, en el presostato y en los instrumentos de medición	Validar	224	224

Fuente: El autor.

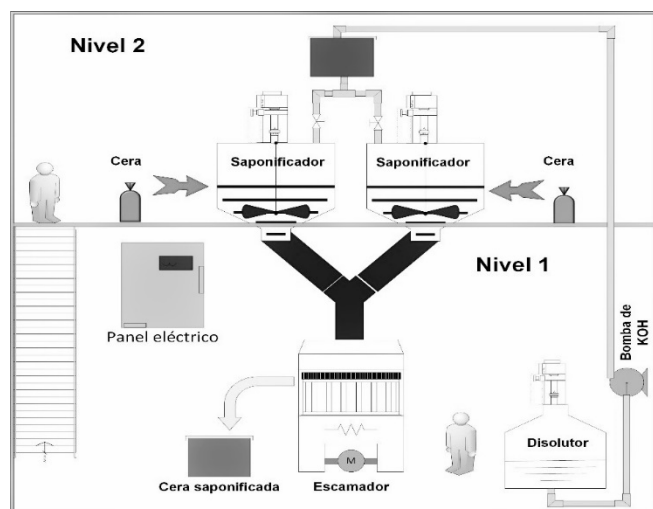


Figura 3. Proceso de saponificación.

Fuente: El autor.

El AMFEC permite identificar potenciales modos de falla y la severidad de sus efectos, las características críticas de los componentes y auxilia a los especialistas a identificar y priorizar productos y procesos, previniendo la ocurrencia de problemas. En la empresa bajo análisis los resultados del AMFEC permiten demostrar ante entidades regulatorias competentes, el control de cada elemento que forma parte del proceso productivo mediante documentos y acciones de seguimiento tomadas para reducir los riesgos. Adicionalmente el departamento de mantenimiento se auxilia de los resultados obtenidos en el AMFEC para la solución de problemas que pueden no haber sido considerados en la etapa de diseño de la tecnología; así como aumentar la seguridad, la disponibilidad y reducción de costos de mantenimiento.

Esta técnica permite al grupo de validación de la empresa, entre otras, establecer evidencia documentada, con alto grado de confiabilidad, de que un proceso específico proporciona en forma consistente un producto que cubre con las especificaciones predeterminadas y sus atributos de calidad.

La Fig. 1 muestra el árbol de falla para el reactor químico. Los árboles de fallas son representaciones gráficas organizadas que representan los factores causantes de un resultado adverso, definido como evento máximo. En el estudio se utilizó con el objetivo de representar de forma gráfica la secuencia de eventos que provocan la falla final del activo después de aplicar las medidas de control. En otras palabras es la técnica que se utilizó para la supervisión y control del riesgo residual.

Esta técnica combinada con el análisis de modo de falla y efectos trae consigo diversos beneficios. El árbol de falla analiza cómo se llega al evento máximo y el análisis de modos de falla y efectos lo analiza desde sus eventos básicos. La combinación de técnicas deductivas e inductivas facilita el entendimiento y mejoramiento de los sistemas.

Adicionalmente existe una consistencia entre las dos técnicas:

Cualquier identificación de una falla en AMFEC tiene que ver con el evento máximo en un AAF, y esta identificación se toma como un punto singular de falla.

Cualquier punto singular de falla deberá ser identificado en el análisis de AMFEC.

El resultado de la implementación de los métodos anteriores, forma parte de las etapas de análisis y evaluación en el sistema de gestión de riesgo de la empresa.

La Fig. 2 muestra el mapa de riesgo de la empresa una vez concluido en proceso de análisis y evaluación de riesgo. Esta técnica permite visualizar de forma gráfica y resumida los elementos críticos en el sistema de forma cualitativa. En el estudio se representaron en el mapa de riesgo general los equipos y sistemas cuyo NPRR es superior a 120, equipos críticos y semi-críticos. Según la metodología planteada se pueden tomar diversas acciones para controlar el riesgo residual de la tecnología, como es el caso de la validación, la calificación o la confección de procedimientos de mantenimientos preventivos. En el caso bajo análisis se caracterizó una variedad de 47 equipos y 8 sistemas de distribución/generación, lo que representa un total de 849 elementos sujetos a evaluación en el proceso. Del total de equipos analizados se incluirán solo en el cronograma de validación el 9% de los mismos, se recalificarán el 13% de los sistemas y se le confeccionará o modificará los procedimientos de mantenimiento preventivos al 2% de los elementos de la empresa, ver Tabla 7.

La metodología aplicada permite re-direccionar, de esta forma los esfuerzos de trabajo hacia aquellos equipos, sistemas, elementos o partes que representen un alto grado de riesgo para el proceso productivo. De esta forma es posible obtener un criterio para definir el intervalo o frecuencia de validación de los activos de la empresa.

Se comienza con una valoración del riesgo sin medidas de control con el objetivo de obtener el número de prioridad de riesgo **NPR**, a través de la cuantificación de los valores de severidad, ocurrencia y detección de la falla potencial. Posteriormente se realiza un análisis de los modos de fallo, de sus efectos y criticidad según la técnica AMFEC y se reevalúa el **NPRR** teniendo en cuenta aspectos de seguridad asociados a los activos, sistemas productivos y el medio ambiente. En este paso es posible utilizar cualquier técnica los métodos fundamentales siempre que permita la reevaluación del riesgo después de aplicadas las medidas de control. Se finaliza con una representación gráfica que proporciona información valiosa en la investigación de problemas y riesgos potenciales, de aquellos activos cuyo **NPRR** es superior a 120.

Según los resultados del análisis, y en consonancia con las normativas establecidas por la autoridad regulatoria nacional CECMED (Centro de Control Estatal de Medicamentos, Equipos y Dispositivos Médicos) se fija como tiempo máximo los siguientes períodos [25]:

- ✓ Tiempo máximo de validación 4-5 años (equipos críticos y semicríticos),
- ✓ Tiempo máximo de calificación 2-3 años (equipos semicríticos),
- ✓ Actualización de procedimientos de mantenimiento preventivo cada 5 años (equipos semicríticos).
- ✓ No obstante, siempre y cuando el proceso sufra una modificación considerable, debidamente documentado y justificado en el sistema de gestión de riesgo de la empresa; se procederá a reajustar el período de validación o calificación según aplique.

5. Conclusión

En el presente trabajo se trazaron diversas estrategias para evaluar el proceso de gestión de riesgo de equipos y sistemas en una empresa de producción industrial. El análisis permitió obtener un criterio práctico para proponer las acciones de control, según la técnica de gestión del riesgo residual utilizada. Como resultado final se obtuvo el intervalo de validación según los indicadores cuantitativos y cualitativos utilizados en el proceso de gestión de riesgo. La metodología propuesta permite además de organizar las acciones de trabajo, establecer prioridades en la gestión de la tecnología según los daños ocasionados al personal, a la planta física o al medio ambiente.

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Numerical and experimental studies of compression-tested copper, mortar contact method

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Abstract

Simulation of compression test of copper is made with the mortar contact method and assuming: axial symmetry, multiple point constraint of type plane, concentrate load and coulomb friction. Copper is simulated like isotropic material, elastic until it yields stress, and then like a hardening material with incremental plasticity. Copper behavior was calculated from experiments. Seventeen compression tests without lubrication were carried out to cylindrical samples at room temperature. The Stress vs. Strain relationship was calculated using two friction corrections; the Rowe Correction and the Dieter Correction. It was concluded that the simulation made with the mortar contact method and the Dieter Correction is a good alternative to simulate the compression test, being the differences between the simulation and the experiments lower than 7.33%, the hypothesis of axial symmetric does not keep away the simulation of the reality and new numerical analysis will allow the development of better friction corrections.

Keywords: Compression test; barreling; copper; finite element; mortar contact; friction.

Estudio numérico y experimental del ensayo de compresión del cobre, método de contacto mortero

Resumen

La simulación del ensayo de compresión del cobre se realizó con el método de contacto con mortero y asume: simetría axial, restricción de puntos múltiples de tipo plano, carga concentrada y fricción coulombiana. El cobre se simula como material isotrópico, elástico hasta fluencia, y luego como un material endurecible con plasticidad incremental. El comportamiento del cobre se calculó a partir de experimentos. Se realizaron diecisiete ensayos de compresión sin lubricación a muestras cilíndricas a temperatura ambiente. La relación Esfuerzo vs. Deformación se calculó usando dos correcciones por fricción; La Corrección de Rowe y la Corrección Dieter. Se concluye que: la simulación realizada con el método de contacto con mortero y la Corrección Dieter es una buena alternativa para simular la prueba de compresión, siendo la diferencia entre la simulación y los experimentales inferior a 7,33%, la hipótesis de simetría axial no aleja la simulación de la realidad y nuevos análisis numérico permitirán el desarrollo de mejores correcciones por fricción.

Palabras clave: Ensayo de compresión; abarilamiento; cobre; elemento finito; contacto de mortero; fricción.

1. Introduction

Massive metal forming processes deform the piece to compression. Some examples of these processes are: rolling, extrusion, and forging. [1]

The simulations had allowed clarifying the behavior of metals during the industrial processes of forming.

The friction between the piece and the tool is one of the most important variables that affect the forming process. The

frictional force not only determines the forming load, but it also influences the workpiece quality. [2] The first step in simulating the friction is to define the contact pair. In this paper the contact pair type mortar contact was assessed.

Mortar contact is a simple and consistent formulation method. [3] It is a surface-to-surface method which usually leads to better convergences and a more uniform stress field. [4]

The contact pair will define the type of friction between the faces. Generally the friction is classified into three types:

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quasi-static dry friction; dynamic and sliding friction; and wear and plowing. [5]

A friction mechanism of type II was used for this study, dynamics and sliding friction.

Dynamic and sliding friction describes, principally, two friction mechanisms: Dry sliding friction of metallic bodies and Stick-slip motion. [5] In this work we used the first one.

Dry sliding friction or Coulomb friction takes: the compressive normal force N and the coefficient of friction μ , to obtain the friction force F . [5]

Mortar contact method has been studied by many authors.

Christian Weißenfels et al. [6] in 2015 proposed a new contact element, and for the discretization of the new contact element the Mortar method was chosen

Tod Laursen et al. [7] in 2012 published a study on the last 15 years of Mortar Contact method. The study shows how this method has improved since a basic summary of the mortaring idea to the extension of these methods to large deformation, large sliding, and the newest results where it can be extended to a much broader class of interface mechanics applications.

Bin Yang et al. [8] in 2005 presented the results of their studies on the mortar contact methods for large deformation with frictional sliding. They concluded that the mortar method has shown to preserve optimal convergence rates in tied contact problems.

Thiago Doca et al. [9] in 2014 introduced a new approach based on a mortar formulation and the enforcement of contact constraints. Their conclusion centered on the accuracy and efficiency of the approach against the traditional node-to-segment penalty contact formulation.

This paper presents the simulation of compression testing using the Mortar Contact method. It was concluded that the aforementioned method allows describing to a great extent the compression test, being the maximum differences between the simulation and the experiments 7.33 %.

The novelty of this paper evolves around the importance of applying the multiple point constraint of type plane condition. This condition avoids the Flash in the sample. The Flash effect is observed, for example, on friction welding.

2. Experimental procedure

The copper was characterized by atomic emission spectroscopy with the Spectro LAB Junior and with metallographic microscope. The characterization showed a 99.9 % purity in copper with an average grain size of 80 μ m.

Seventeen compression tests were performed without lubrication, with a speed of 0.028 mm/s, and an acquisition rate of 175 data per second. Compression tests were performed according to the specifications of ASTM E 9-09A [10] with the universal testing machine MTS-312.31/227. The copper samples were of 12.6 mm of diameter and 20 mm of height.

The displacement of the load cylinder of the testing machine was the variable. The first compression test was made up until a displacement of 2 mm was achieved, thus causing the displacement to increase up until reaching 14mm during the last test.

Fig. 1 is a photo of some samples tested.



Figure 1. Photos of samples tested, the first is the standard sample, and the following were compressed with loads of 4160, 4878, 5878, 7050, 8771, 11530 and 16067 Kgf. (tests 2, 4, 7, 9, 11, 14, 16 in the Figs. 2 and 3). Source: The author.

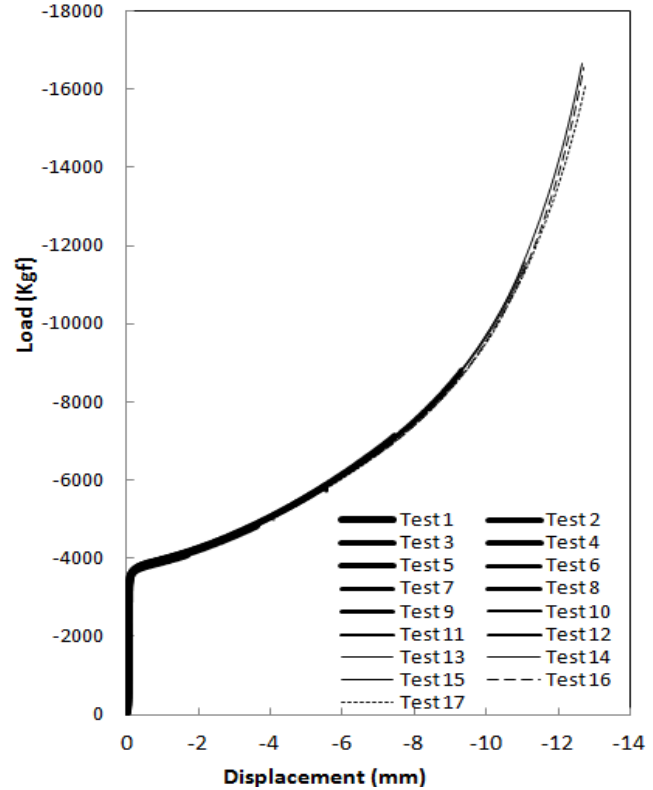


Figure 2. Load vs. Displacement of the seventeen compression tests. Source: The author.

The diagrams of Load vs. Displacement are shown in Fig. 2 and the lengths measured and where they were taken (Fig. 7) on the specimens obtained from these tests are showed with points in the Figs. 8, 9 and 10.

The Stress and Strain were calculated with the following Equations:

$$\sigma_i = \frac{L_i}{A_i} \quad (1)$$

$$\varepsilon_i = \ln \left(\frac{A_0}{A_i} \right) \quad (2)$$

$$h_0 A_0 = h_i A_i \quad (3)$$

$$h_i = h_0 + \Delta L_i \quad (4)$$

Where σ_i is the instant stress, ε_i is instant strain, L_i is the instant load, h_0 , A_0 , h_i and A_i , are the initial height, initial area,

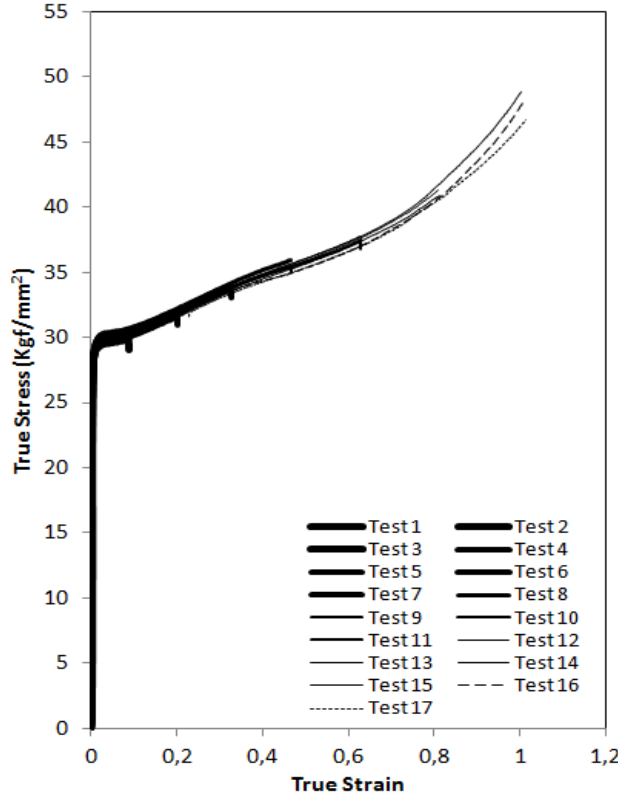


Figure 3. Stress vs. Strain diagrams of the seventeen compression tests calculated with the volume conservation principle.
Source: The author.

instant height and instant area of the sample, respectively; Δl_i is the displacement, and the instant area A_i is calculated with the volume conservation principle (Eq. 3).

Fig. 3 shows the diagrams of Stress and Strain of the seventeen tests, calculated with Equations 1 to 4.

Fig. 2 shows the superposition of all the curves of the seventeen tests.

The superposition of all the curves is in the Fig. 3 too.

The superposition of all curves in Figs. 2 and 3 show the repetitiveness of the tests.

Two friction corrections are used to obtain an approximation for the copper behavior in compression. The Rowe Correction can be written as Eq. 5 [11] and the Dieter Correction as Eq. 6 [12], these relationships are, respectively:

$$\sigma = \frac{\sigma_z}{\left(1 + \frac{2f}{3\sqrt{3}} \frac{r_i}{h_i}\right)} \quad (5)$$

$$\sigma = \frac{C_f^2 \sigma_z}{2 \left[\exp(C_f) - C_f - 1 \right]} \quad (6)$$

Where r_i is the instantaneous values of radius, calculated from A_i (Eq. 3), σ and σ_z ($\sigma_z = \sigma_i$ in Eq. 1) are the Equivalent axial stresses without and with the frictional condition (these last ones

are taken from Fig. 3); f is the Tresca Friction Coefficient and it is Equal to $f = \sqrt{3}\mu$, C_f is the Coulomb stress distribution and is $C_f = 2\mu r_i / h_i$. These Equations are for cylindrical sample and they assume that the barreling is negligible; σ and σ_z are constants throughout the sample height. [13]

The friction coefficient between copper and steel has been estimated on 0.53 for static friction and 0.29 for sliding friction. [14] Figs. 4 and 5 show the results of friction corrections for a bigger range of friction coefficients.

Fig. 4 shows diagrams of Stress vs. Strain of the test 16 and those obtained with Rowe Correction (Eq. 5).

Fig. 5 shows the diagrams of Stress vs. Strain of test 16 and those obtained with Dieter Correction (Eq. 6).

Figs. 4 and 5 show that while the lower the friction coefficient value is, the stresses obtained with the frictional condition will be closer to the stresses calculated without this condition, but when higher values of friction coefficient are supposed, the real strength of the material will be lower.

3. Numerical simulation

The mesh was made with Gmsh [15] and the simulation was made with Calculix [4], both are open softwares. The simulation was carried out with a HP Pavilion dv6.

The control volume of the simulation is the middle bottom of the sample and the bottom dice (see Fig. 6). This is because we took the hypothesis of axial symmetry, the behavior of the top side is the same as its bottom side.

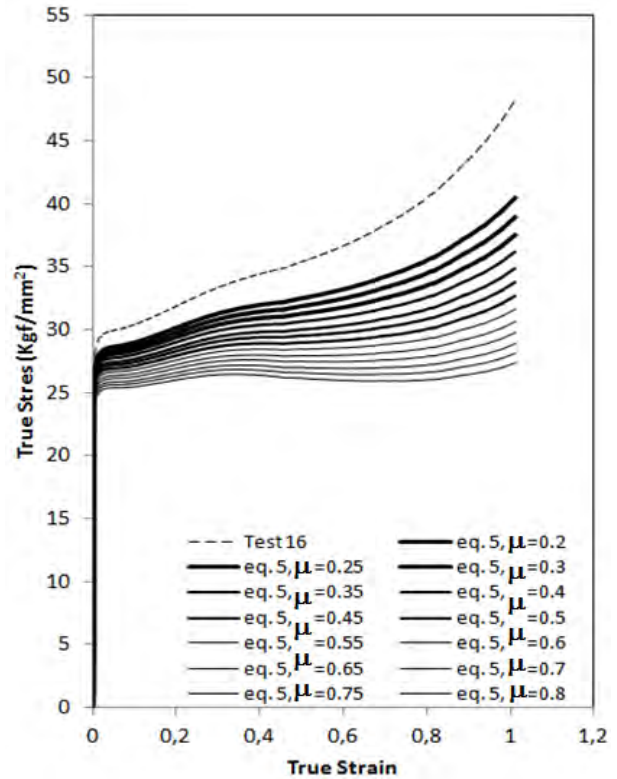


Figure 4. Stress vs. Strain calculated with the Rowe Correction to test 16.
Source: The author.

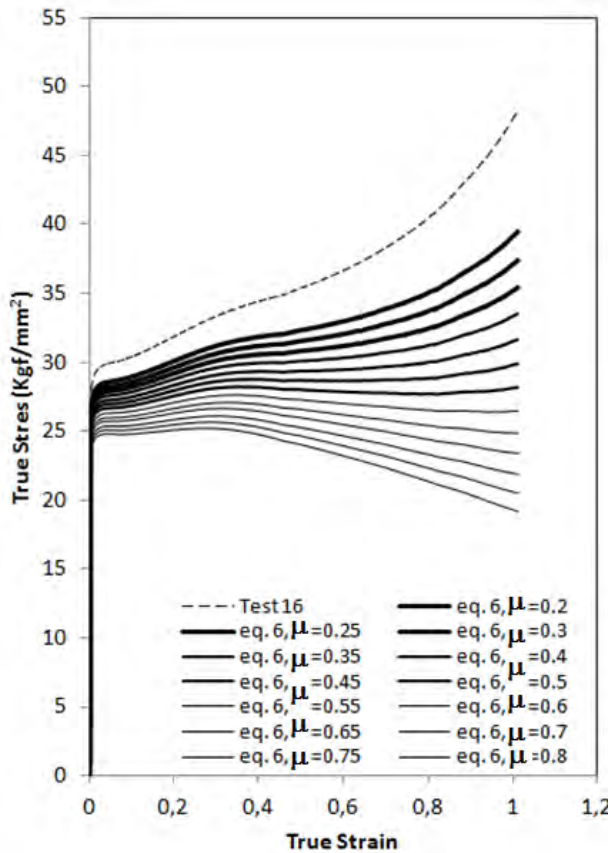


Figure 5. Stress vs. Strain calculated with the Dieter Correction to test 16. Source: The author.

Rasta *et al.* [16] in 2011 measured experimentally that symmetry in compression test. Chen *et al.* [17] and Raja *et al.* [18] used that symmetry like a boundary condition in their numerical simulations.

Two solids were defined: the first one is for the dice and the second is for the copper samples.

The dies of the universal testing machine are and were simulated like tempered steel AISI-4140, and its behavior, in the load range, is isotropic linear elastic. This behavior is described by the Young Modulus (E) and the Poisson Coefficient (ν), [19] being the Young Modulus 22000 Kg/mm² [20] and the Poisson Coefficient 0.29 [21].

The copper sample was modeled like an isotropic material with linear elastic behavior until the yield stress; and then an incremental plasticity material with hardening. [22] The Young Modulus and a Poisson Coefficient are 11000 Kg/mm² [20] and 0.34 [21], respectively. The plastic behavior is described by the Von Mises Stress (σ_{VM}) and the Equivalent Strain (ϵ_p). This plastic behavior was calculated by three different ways.

The first one takes the mechanical behavior from the volume conservation principle (test 16 in Fig. 3). The results of this simulation are shown in the Fig. 8.

The second and third simulations take the mechanical behavior from the Eq. 5 (Rowe Correction) and Eq. 6 (Dieter Correction), respectively, (see Figs. 4 and 5). The results of these simulations are shown in the Figs. 9 and 10.

The simulation has boundary conditions in three surfaces: (see Fig. 6)

a) *The surface of middle of the copper sample.* This surface is free to move and over it a compression load is applied that goes from 0 to 16000 Kg. This load is simulated like a concentrate load, 222 Kg for each 72 nodes of this surface, giving approximately a total load of 16000 Kg (see Fig. 6). Another condition on this surface is the multiple point constraint of the type plane (MPC-PLANE). This MPC-PLANE specifies that all nodes in this surface should stay in a same plane. Note that this plane can move during deformation, depending on the motion of the defining nodes. [4] This last condition avoids ribbon of metals in this surface. This defect of ribbon is also called as Flash (see Fig. 11.c).

b) *The bottom surface of the copper sample.* This surface is free to move and it was defined to complete the contact pair with the top of the bottom die, mortar contact with coulomb friction.

c) *The top surface of the bottom dice.* This surface has no freedom degrees, and it was defined to complete the contact pair with the bottom surface of the copper sample.

Fig. 7 shows where the experimental measures were taken; Figs. 8, 9 and 10 show these measures and simulation results.

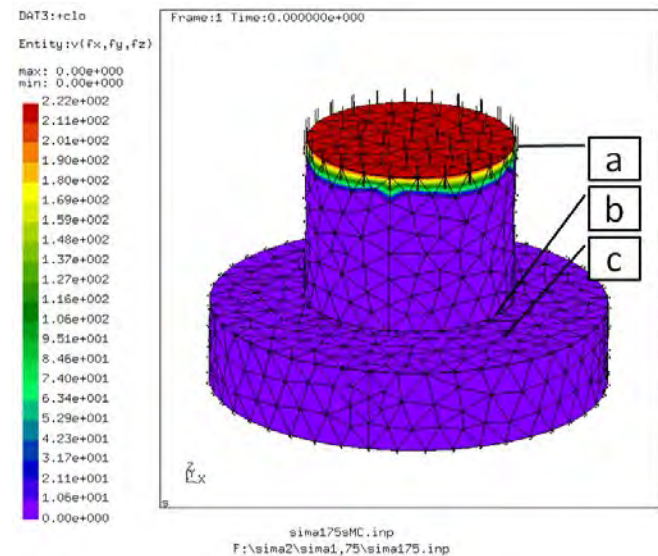


Figure 6. Boundary Condition: (a) The surface of middle of the sample, (b) The bottom of the sample, (c) The top of the lower dice. Source: The author.

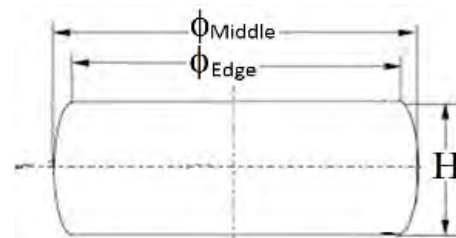


Figure 7. Measurements of the sample: H: height, Φ_{Middle} : diameter in the middle, and Φ_{Edge} : diameter in the edges. Source: The authors.

Fig. 8 shows the simulation results assuming the mechanical behavior of copper obtained directly from principle of volume conservation without any friction correction (Fig. 3).

Fig. 9 shows the simulation results assuming the mechanical behavior of copper obtained with the friction correction of Rowe (Fig. 4).

Fig. 10 shows the simulation results assuming the mechanical behavior of copper as it was obtained with the friction correction of Dieter (Fig. 5).

The simulation shows the behavior inversely proportional of friction with the edge diameter (green lines in the Figs. 8, 9 and 10), nevertheless this effect decreases from Figs. 8 to 10. The middle diameters (brown lines in the Figs. 8, 9 and 10) and the heights (blue lines in the Figs. 8, 9 and 10) have the same behaviors but they are less affected by the friction.

The simulation made with the Dieter Correction (Fig. 10) is the nearest to the experimental measures, with friction coefficients between 0.2 and 0.3. A friction coefficient of 0.3 gives better results for small displacements, being the diameters on the edge and on the middle the same as that of the diameters experimentally measured and a difference between heights of 7.33%, but for bigger displacements a friction coefficient of 0.2 gives better results, being the height the same as that of the height experimentally measured and a difference between the diameters calculated and measured below 5.70%.

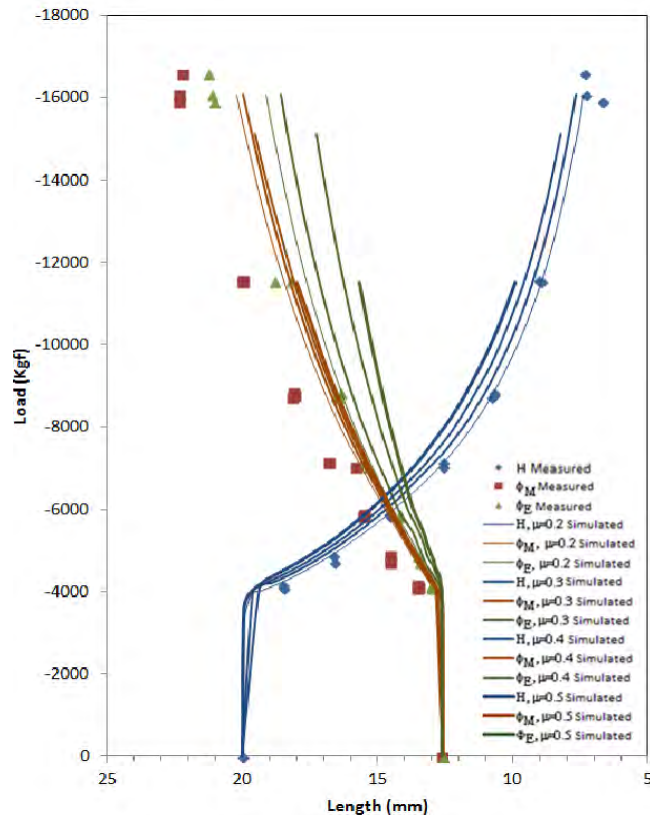


Figure 8. Load vs. Length. The experiments are points and the simulations are lines. The simulation made with different friction coefficients takes the mechanical properties of copper calculated with the volume conservation and without friction correction.
Source: The author.

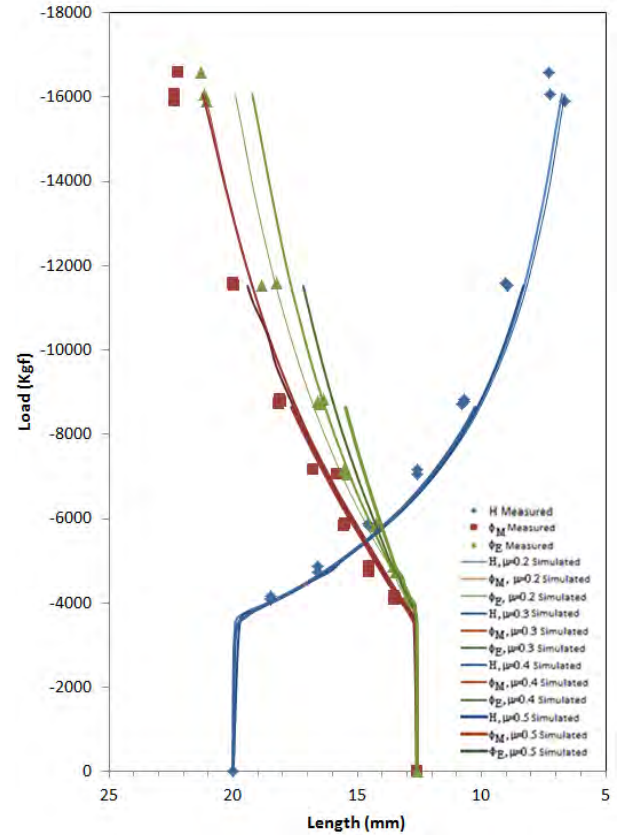


Figure 9. Load vs. Length. The experimental measures are points and the simulations are lines. The simulation made with different friction coefficients takes the mechanical properties of copper calculated with the volume conservation and Rove Correction.
Source: The author.

Fig. 11.a shows the stress on Z for a load of -5878 Kgf.

Fig. 3 shows that the test 7 (Fig. 1), was compressed with a load of -5878 Kgf, Equivalent to 33.75 Kgf/mm² (see Fig. 4). This stress for this load (Fig. 11.a) is in the point (a). This was expected because the instant areas were calculated with the volume conservation principle.

Fig. 11.b shows the stress on X for a load of -5878 Kgf. The stress on X is zero in the middle of the sample; this is one of the hypotheses searched with boundary conditions in this surface.

Fig. 11.c shows the displacement on Z for a load of -5878 Kgf without MPC-Plane condition. The Fig. 11.c shows the Flash on the top.

Fig. 12.a shows the stress on Z for a load of -16000 Kgf.

Figs. 11.a and 12.a show that for loads of -5878 and 16000 Kgf, the stresses on Z in the middle of the sample (the tops in the Figures) gave approximately 29.5 and 39.5 Kgf/mm², respectively, see point (b) in Fig. 11.a. These values of stresses for these loads are similar to the obtained with the Dieter Correction, 30.34 and 39.47 Kgf/mm². Therefore the mechanical behavior obtained with the Dieter Correction is nearer to the reality than the Rowe Correction.

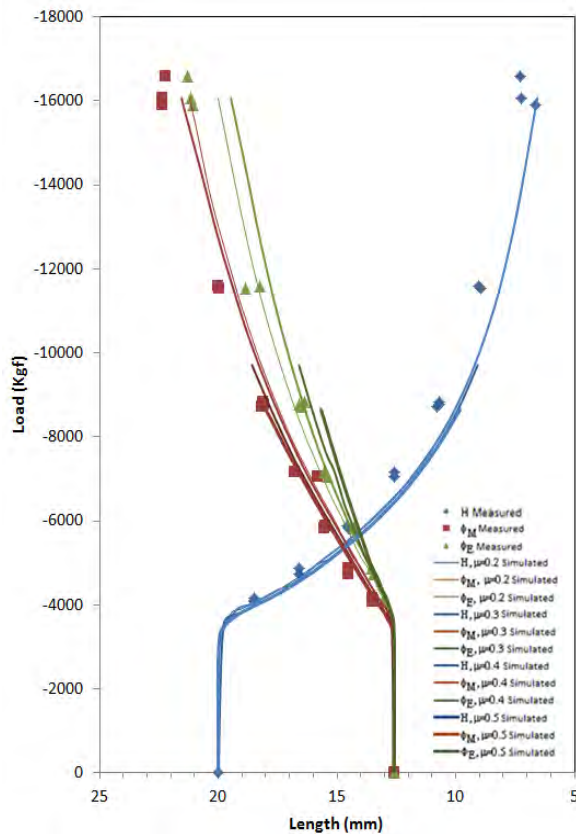


Figure 10. Load vs. Length. The experiment measures are points and the simulations are solid lines. The simulation made with different friction coefficients takes the mechanical properties of copper calculated with the volume conservation and Dieter Correction.
Source: The author.

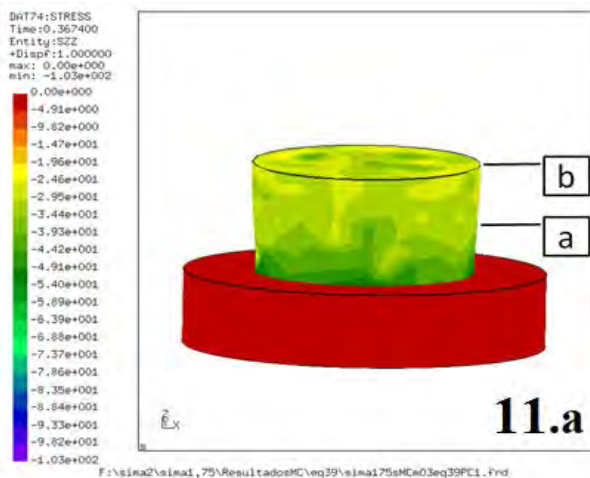


Figure 11.a. Stress on Z (Kgf/mm²). Dieter Correction is assumed, $\mu=0.3$ and the $L=-5878$ Kgf ($16000 \cdot 0.3674$).
Source: The author.

A better knowledge on the barreling during compression of cylindrical samples will enable predicting the behavior of the sample diameter. That will enable obtaining the instant area in the middle of the sample and calculate the true

stresses. This would make it possible to define new and better friction correction and improve the simulations of forming processes.

Fig. 13 show the validation of the mesh. The most refined mesh with convergent results is one with an element size factor of 1.75.

4. Conclusions

The Dieter Correction and Rove Correction show that while the lower the friction coefficient value is, the stresses obtained with the frictional condition will be closer to the stresses calculated without this condition, but when higher values of friction coefficient are supposed, the real strength of the material will be lower.

The hypothesis of axial symmetry, that the behavior on the top side is the same as on the bottom side, does not make the simulation move away from the reality.

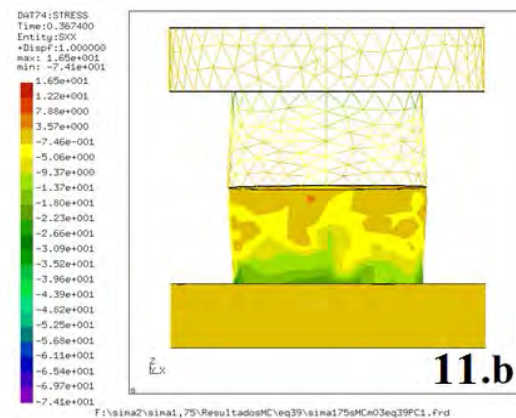


Figure 11.b. Stress on X (Kgf/mm²). Dieter Correction is assumed, $\mu=0.3$ and the $L=-5878$ Kgf ($16000 \cdot 0.3674$).
Source: The author.

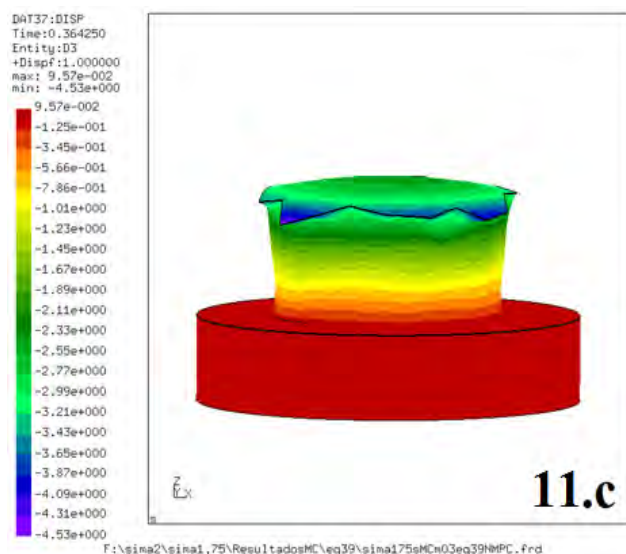


Figure 11.c. Displacement on Z (mm). Dieter Correction is assumed, $\mu=0.3$ and the $L=-5878$ Kgf ($16000 \cdot 0.3674$).
Source: The author.

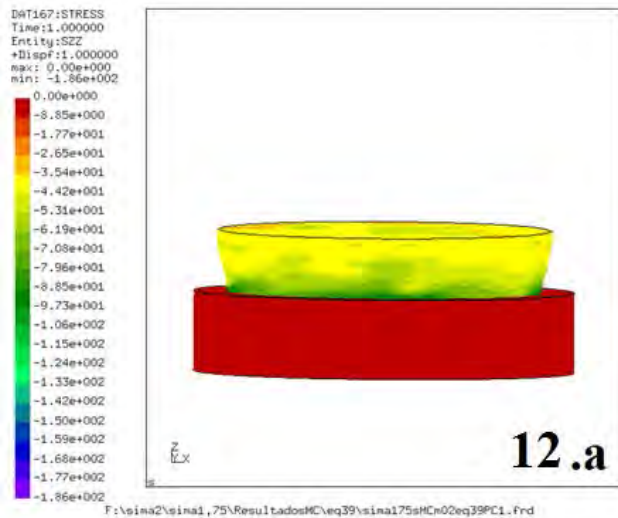


Figure 12.a. Stress on Z (Kg/mm²). Dieter Correction is assumed, $\mu=0.2$ and the $L=-16000$ Kg (16000*1).
Source: The author.

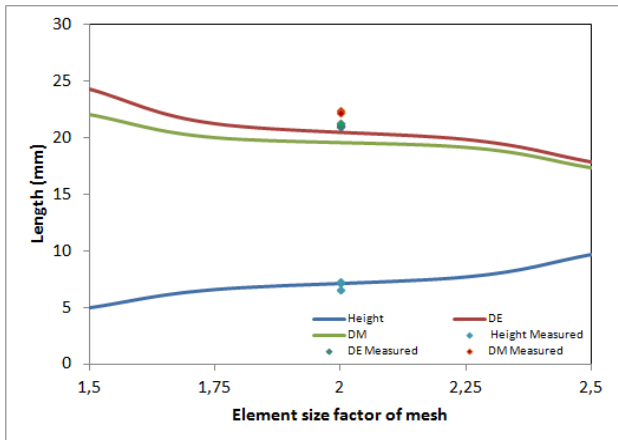


Figure 13. Validation of the mesh. Simulations made with Dieter Correction, $\mu=0.3$ and $L=-16000$ Kg.
Source: The authors.

The boundary condition of MPC-Plane in the middle of the sample is necessary to void the flash in the sample when the axial symmetry is a hypothesis in the simulation.

The simulation of the compression test obtained with the Dieter Correction is nearer to the experimental measures than the simulation obtained with the Rove Correction. The differences between the experimental measures and the simulation made with the Dieter Correction are below 7.33%. The Mortar Contact method describes with a good precision the behavior of the copper when it is compressed with open dies.

Numerical analysis on the barreling of the samples during the compression in open dies will allow the development of better friction corrections.

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Immobilization of recognition elements on a self-assembled monolayers bio-platform

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Abstract

Tailored materials formed by spontaneous two-dimensional arrangement of 3-aminopropyltriethoxysilane self-assembled monolayer on glass (amino-functionalized glass) has been exploited to attach biomolecules in well-organized structures useful in biosensing. Succinimidyl ester of both unpolymerized diacetylene liposome (NHS-DA-liposome) layer and PEGylated biotin (Bt-PEG-NHS) matrix were covalently bonded to the amino-functionalized glass by the NHS linker, and exposed to either Tyrosinase (Ty) or Streptavidin (SAV) solution. The interaction between Ty and polymerized NHS-PDA-liposome transformed the planarity of the PDA backbone, and a blue-to-red transition occurred; Bt-PEG attached to the fluorescent-SAV by bioaffinity. Sensing capability of bioplatfrom systems was evaluated by Uv-vis spectroscopy or fluorescence microscopy. Biomolecule functionalized SAMs retained the recognition potential of colorimetric Ty-PDA-liposome after biological interaction, and also facilitated the fabrication of a protein-resistant matrix with a particular affinity property. This surface chemistry is accessible to depositing proteins on both SAM-coated glass surface, and tethered to SAM, resulting in optical bioplatfrom arrays.

Keywords: functionalized surface; biosensor; polydiacetylene liposome; biotin-streptavidin; 3-aminopropyltriethoxysilane.

Inmovilización de elementos de reconocimiento en una bio-plataforma basada en capas auto-ensambladas

Resumen

Los materiales funcionalizados por adsorción sobre capas autoensambladas de 3-aminopropiltriétoxissilano (APTS) en vidrio (vidrio amino-funcionalizado) sirven para inmovilizar biomoléculas en estructuras usadas para biosensores. Liposomas de polidiacetileno (lip-PDA-NHS) y Biotina PEGilado con NHS se inmovilizaron aprovechando el éster de succinimidilo; y sirvieron para reconocer Tirosinasa o streptavidina (SAV). Debido a la interacción liposoma-PDA-Ty, ocurrió un cambio en la planaridad de la cadena polimérica PDA, percibido como una transición de azul-a-rojo; mientras que, la biotina inmovilizada interactuó con SAV por afinidad biológica. La capacidad de detección del sistema se evaluó por espectroscopia UV-vis o por microscopia de fluorescencia. Las capas de APTS funcionalizadas con biomoléculas retuvieron la capacidad de reconocimiento colorimétrico después de la interacción biológica, permitiendo la fabricación de una matriz resistente a proteínas con una propiedad de bioafinidad. Esta química de superficies es simple y accesible para la modificación de sustratos de vidrio, útiles en arreglos de bioplatformas ópticas.

Palabras clave: superficie funcionalizada; biosensor; liposomas de polidiacetileno; biotina-estreptavidina; aminopropiltriétoxissilano.

1. Introduction

The analytical signal of biosensors is generally proportional to the number of recognition events occurring at the interface, involving the interactions between biomolecules and ligands. Accordingly, the surface coverage

contributes to regulate the extension of the interfacial interactions with target molecules, resulting in a change of a specific physical property; which is then perceived by the transducer element, turning it into a measurable analytical signal. [1]. In an optical biosensor, tuning the interplay of specific response can be reached by surface functionalization

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with chemical or biological coupling agents, to keep the recognition elements on top of the surface. The nanostructures self-assembled monolayers (SAMs) are formed by appropriate interactions between molecular constituents that organize themselves in a stable and well-defined array on different substrates. [2]. The surface-induced order and stability of SAMs impart definite properties on a molecular level, making them useful for improving control of adhesion, wettability, detergency, isolating, friction and lubrication processes, as well as for detecting biological activity in biosensors. [3]

SAMs on glass, a translucent substrate, provide the tailored surface required to sense the analyte, leading to a change of colorimetric or fluorescence emission properties. Alkyl trichlorosilanes have been used to form SAMs on glass, a cheap and widely available material; however, considering that they are susceptible to hydrolysis, alkyl triethoxysilanes substitute them in fabrication of SAMs on silica, metal and glass substrates. [4]. For example since 1969, a simple preparation method based on 3-Aminopropyltriethoxysilane (APTS) is used to form SAMs on glass. [5,6] APTS molecule contains the siloxane group that anchors the molecule on the hydroxylated glass by in situ formation of polysiloxane, which is connected to surficial silanol groups (-SiOH) via Si-O-Si bonds; the attained APTS-SAMs exhibit high stability, and resistance to increased temperature; but they have a strong trend to form multilayers. [7]

The functionalized glass displays a terminal amine group capable of direct coupling with N-hydroxysuccinimidyl linker (NHS), operating as scaffolds to control the spontaneous formation of more complex structures of determined composition. [8]. Thus, amino-functionalized glass provides a path for chemical derivatization, offering the possibility to carry hydrophobic, polar, or reactive functional groups for selective binding of guest molecules. [9]. Covalent immobilization of ligands to evaluate both biomolecule detection, and attachment points of biomolecules, provided by SAMs, has direct implications for the development of optical biosensors. Resulting in application of two biosensing approaches, for detecting protein targets, and for studying processes dependent on immobilized protein. [10]

This paper presents amino-functionalized glass surface for supporting both optical sensing approaches: Attachment of colorimetric polydiacetylene (PDA) liposomes modified with an enzyme, that are capable to bind the substrate and undergo a color transformation after stimuli, as a result of changes in the planarity of the polymer backbone; [11] and immobilization of a ligand that recognizes by bioaffinity a particular fluorescent-labeled enzyme, it system shows resistance to the unwanted adsorption of other proteins based on a passive surface of polyethyleneglycol (PEG). [12]

2. Materials and methods

2.1. Chemical reagents

All 3-aminopropyltriethoxysilane (APTS), ethanol (EtOH), hydrochloric acid (HCl), sulfuric acid (H₂SO₄), 30% hydrogen peroxide (H₂O₂), tyrosine, sodium carbonate

(Na₂CO₃) and sodium bicarbonate (NaHCO₃), and 10 mM sodium phosphate buffer (PBS), pH 7.4 was prepared from sodium hydrogen phosphate, potassium dihydrogen phosphate, and 150 mM sodium chloride which were purchased from Sigma Aldrich. 10,12-pentacosadiynoic acid (DA) was acquired to FSG inc., and Dimiristoyl Phosphocholine was acquired to Avanti Polar. Biotin-PEG5000-succinimidyl ester (Bt-PEG-NHS) was obtained from Pierce Biotechnology. Tyrosinase (Ty) and streptavidin Fluorescein isothiocyanate conjugated (FITC-SAV) was brought in Invitrogen, Molecular Probes. Nanopure water was supplied from a Simplicity MilliporeQ system (Conductivity 6 μ S/cm). Diacetylene-succinimidyl ester (DA-NHS) was obtained as a kind gift from Dr. Punit Kohli.

2.2. Preparation of amino-functionalized glass slide

The surface of the glass slides previously activated in solution piranha (H₂SO₄ and H₂O₂, 7:3 v/v) for 1 hour, was rinsed with nanopure water and dried under a nitrogen stream. Then, it was silanized in a beaker containing APTS in acid ethanol solution APTS:EtOH:HCl of 98.8:0.2: 1, for one and a half hours at room temperature. [13] Two aliquots of 5 mL of EtOH were used to eliminate excessive reagent from the surface and a nitrogen stream was applied. The slides were rinsed with 5 mL of 10 mM PBS, pH 7.3. Contact angle (CA) was evaluated by the advancing drop DMS-200 and calculated by the tangent method.

2.3. Immobilization of biostructures on functionalized glass slide for protein binding

2.3.1. Preparation of NHS-PDA liposome on amino-glass slide

1 mM liposome modified with NHS in 10 mM PBS, pH 7.3 solution was synthesized by a literature method. [14] Briefly, 0.0123 g of DA and 0.0040 g of DA-NHS dissolved in 25 mL dichloromethane were mixed and filtered. The filtrate was transferred into a round bottom flask containing 0.0060 g of DMPC in 25 mL of dichloromethane. Then the solid obtained by rotoevaporation, was dissolved with 50 mL of 10 mM PBS (pH 7.3), sonicated at 75 °C for 15 minutes and the NHS-DA-liposome solution was kept at the refrigerator for eight hours. 250 μ L of this unpolimerized liposome solution were incubated by 60 minutes on the amino-functionalized glass. [15]. The immobilized NHS-DA-liposomes on glass slide were polymerized by 1, 3, and 5 minutes under a 254 nm UV light in an ice bath. The attachment of polymerized liposomes (NHS-PDA-liposome) on the glass surface was evidenced by heating the slide at 100 °C on a hot plate instrument. Uv-vis spectra were obtained with a Genesys 10 spectrophotometer before and after of thermal stimulus, in the range 400-700 nm.

2.3.2. Preparation of Bt-PEG on amino-glass slide

The biotin was covalently tagged to the amino-functionalized glass slides by adding 100 μ L of 2 mM Biotin-PEG5000-NHS dissolved in 50 mM carbonate buffer, pH 8.3,

onto amino-functionalized glass, for 30 min at room temperature. The biotin modified glass slides were then washed sequentially with 10 mL aliquots of 10 mM PBS solution, nanopure water and dried under a stream of nitrogen. [16]

2.4. Colorimetric detection of proteins by NHS-PDA-liposome-glass slide

250 μ L of 10 μ M of Ty was deposited onto NHS-PDA-liposome-functionalized glass slide, at room temperature for 30 minutes. UV-vis spectra before and after binding event were obtained. [17]

Activity of immobilized Ty onto PDA-liposome-functionalized glass slide was evaluated for substrate detection. In a separated experiment, unpolymerized and immobilized liposomes on SAM glass interacted with Tyrosinase solution under similar conditions. Then, polymerization of Ty-DA-liposomes on glass slide occurred under 254 nm UV light. The resultant system Ty-PDA-liposome functionalized glass slide was exposed to 250 μ L of 1 mM Tyrosine in 0.1M phosphate buffer (pH 7.0) at 25°C. UV-vis spectral changes before and after interaction were monitored spectrophotometrically. [18]

2.5. Detecting proteins by Fluorescent emission using Bt functionalized glass slide.

The coating of Biotin-PEG5000-functionalized glass slide was in contact with 200 μ L of 2 μ M FITC-SAV solution prepared in 0.1 M PBS, pH 7.3 for 30 minutes. [19] Resultant FITC-SAV-Bt at top of the functionalized glass was evaluated by fluorescence emission of the FITC in the air using an inverted fluorescent microscope (Leica DMIRB) equipped with a Nuance (Perkin-Elmer) multispectral imaging system and 515 long pass emission filter (N2.1, 513 832) under the 20X objective and filter No 2.

3. Results and Discussion

3.1. Silanized glass surface

Different solid supports could be used to prepare optical sensing surfaces. Especially glass is a readily available and inexpensive support media, holding a relatively homogeneous chemical surface susceptible to chemical modification by silanization chemistry. SAM on glass provides detection capabilities in the UV-visible range and also in fluorescence emission for biosensors. The importance of proper surface modification are displayed by SAM-glass, keeping active the probe molecules such as immobilized proteins, and suppressing of non-specific binding in optical sensors. Fig. 1 presents the scheme for gradual adaptation by chemisorption and self-organization of alkyl molecules on the surface of a glass substrate depending of the sensing use of this surface. Fig. 1, scheme a) shows the activation step by hydroxylation of glass and silanization by chemisorption, the amine terminal group is exposed at top; scheme b) presents the preparation step of NHS-PDA-liposome-functionalized glass slide, immobilization of NHS-DA-liposome, followed

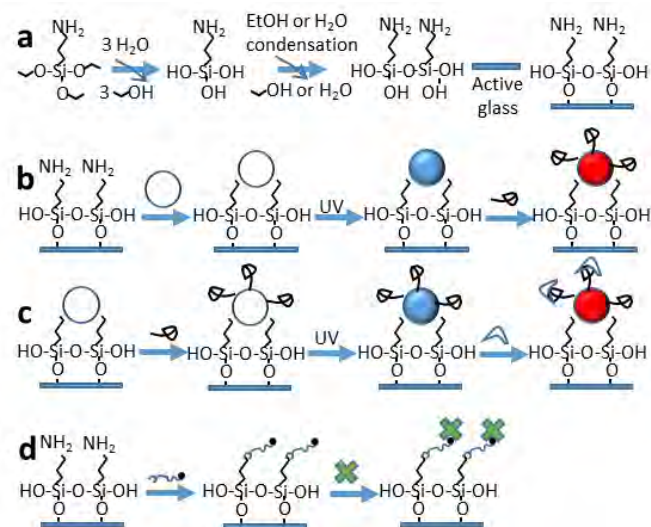


Figure 1. Probe biomolecules functionalized SAM on glass surface for sensing purposes. a) Preparing a glass surface by chemisorption of SAMs, b) Immobilized liposome, then polymerization (PDA-liposome) for sensing enzyme binding, leading a transformation blue-to-red PDA, c) Covalent attachment of liposome modified with enzyme, then polymerization (Ty-PDA-liposome) for substrate-ligand recognition resulting in blue-to-red colorimetric change, and d) Immobilized Bt-PEG-functionalized glass for affinity recognition of fluorescent streptavidin.

Source 1a: [20]; and Source 1b-d: The authors.

by UV polymerization; then Ty detection with transformation blue-to-red PDA; scheme c) shows activity of Ty onto NHS-PDA-liposome-functionalized glass slide for substrate detection, immobilization of NHS-DA-liposome, followed by modification with Ty and UV polymerization, then enzyme-substrate interaction, with change from blue-to-red color; and scheme d) presents the preparation of Bt-PEG functionalized glass slide for protein binding, then recognition of FI-SAV with simultaneous blocking of the surface to proteins different to analyte of interest, visualized by the green fluorescent emission.

In this study, functionalized glass was obtained by modification with the coupling agent APTES, a bifunctional organosilane that provides a chemical bond between two different materials, the glass and amine-linkers such as N-hydroxysuccinimidil reagents. The initial self-assembled structure is formed by chemisorption on hydroxylated glass; reaching an equilibrium to the lowest free-energy state of molecules of APTES, which demands a balance between attractive and repulsive molecular forces. [21]

Table 1.
Contact angle of functionalized SAM glass.

Modification	Contact Angle (°)	Contact Angle (°) Literature
Clean glass	20	< 30
APTS-glass	56	58
NHS-PDA-liposomes- APTS-glass	54	57-78
Bt-PEG-glass	51	45

Source: The authors.

3.2. Ligand immobilization by displacement of the NHS ester on the biomolecule with amino group of APTS

Table 1 presents the contact angle (CA) calculated of functionalized SAM glass.

The resultant APTS-glass shows the CA value of 56° with increased hydrophobicity in presence of amino group; in contrast the hydroxylated glass holds the CA of 20° . If the CA parameter of water is less than 30° , the surface is designated hydrophilic since the forces of interaction between water and the surface are close to the cohesive forces of bulk water. [22] The hydrophobicity of short chain of APTS can be attributed to films with less ordered extension because three possible reasons, *i*) the reduced van der Waals interactions between adjacent hydrocarbon chains; [23] *ii*) the produced monolayer consists of a cross-polymerized network of molecules with only a few bonds to the surface; [24] and *iii*) some amino groups can interact with the silica surface instead to water. [25]

Next, APTS-glass interacted with either reactive liposomes containing NHS at surface or the heterobifunctional polymer Bt-PEG-NHS with the polyethyleneglycol as a flexible linker and biocompatible spacer. The remain NHS groups on the attached liposome are chemical ligands available to interact with amine groups from lysine residues; the ligand Bt directs the specific recognition sites with the streptavidin protein, by affinity or electrostatic interaction and PEG keeps the surface free of another interactions. [26] Wettability of surface was evaluated by CA parameter, in presence of liposomes, or with the polymer PEG, the resultant CA values of 54° and 51° , respectively agree with lower hydrophobic property of the surface. CA data compare well with the values found on similar SAM, high hydrophobicity of 58° for APTS and a lighter hydrophobicity accounted for PEG of 45° . [27] For NHS-PDA-liposome functionalized glass, the calculated CA value of 54° is close to the polydiacetylene film range of $57\text{--}78^\circ$ found in literature due to presence of hydrophilic carboxylic and NHS groups. [28]

Also the structure NHS-PDA-liposome was monitored by UV-vis spectra obtained after polymerization. Fig. 2 shows the binding of NHS-DA-liposome functionalized glass and the development of the polymerization process at different times of exposition, 1, 3 and 5 minutes by 254 nm light. UV-vis spectra was changing during the polymerization process. Initially unpolymerized diacetylenes do not absorb light in the measured range, 400–700 nm. After the first minute under irradiation, the surface displayed a characteristic band at 640 nm, attributed to $\pi\text{--}\pi^*$ electronic promotion with a vibronic shoulder at 580 nm, the blue PDA, resulting of the overlap of the adjacent π -orbitals, a conjugated and planar arrangement that accumulates stress in the structural backbone. [29] The spectra kept the shape, and intensity of blue PDA was increased as polymerization time was prolonged. After 5 minutes of UV irradiation, the spectra shows a new band around 540 nm, excessive irradiation energy contributes to rotation of C–C bonds of the conjugated backbone, thus modifying the planarity of the polymer arrangement and promoting a partial distortion of conjugated π -orbitals, that results in higher $\pi\text{--}\pi^*$ band gap and reduces the effective conjugation length of the backbone. This transformation is perceived as an optical change assigned to the red PDA phase. [30]

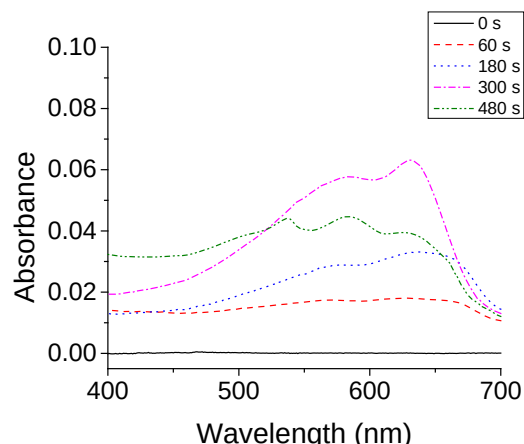


Figure 2. UV-vis spectra of PDA-NHS –lip immobilized on APTS-glass through the polymerization process.

Source: The authors

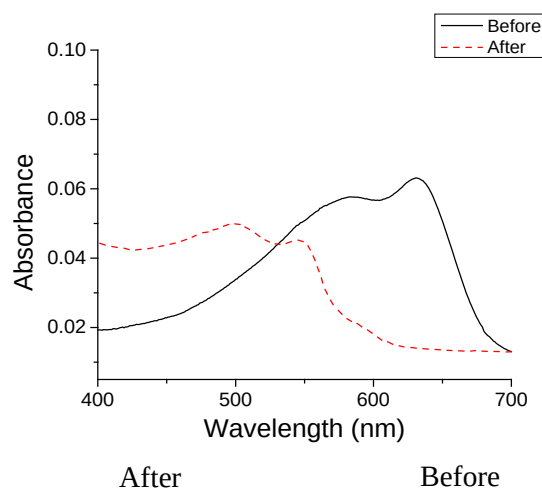


Figure 3. UV-vis spectra of PDA-NHS liposomes sensing thermochromic effect, A) Before, and B) After heating.

Source: The authors

As a proof of PDA-liposome binding to APTS-glass, the UV-vis spectra before and after an experiment by heating the slide of Fig. 3 shows the spectral absorption changes due to heating at 100°C of the NHS-PDA-liposome functionalized glass sensing surface.

The resultant UV-vis spectra changed at 640 nm, where the band intensity decreased and a new band appeared at 540 nm with a shoulder at 490 nm, assigned to emerging of a new red PDA. [31] Fig. 4 shows the Liposome-SAM-glass slide before and after heat process at 100°C .

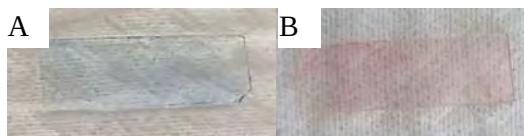


Figure 4. Image of PDA-liposome-functionalized glass slide A) Before, and B) After heating.

Source: The authors.

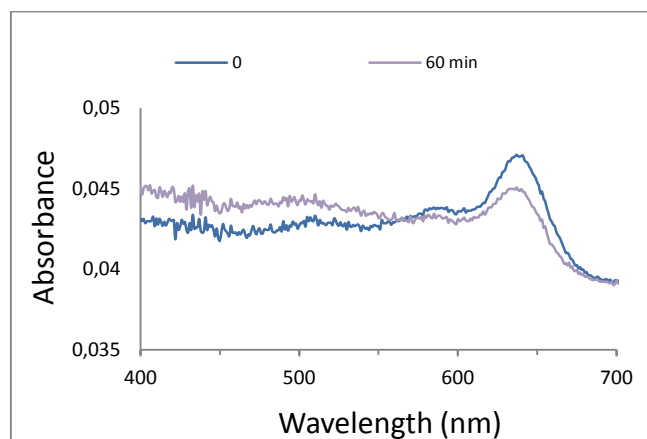


Figure 5. UV-vis spectra of immobilized Ty-PDA-liposome on APTS-glass in presence of substrate tyrosine.
Source: The authors

This immobilization method on APTS SAM provides an alternative to the covalent bond formation between liposomes and glass surface. [32]

3.3. Colorimetric detection of biological activity of functionalized glass

In order to evaluate the activity of immobilized liposomes, the enzyme Ty was covalently attached on the top of the PDA-liposome functionalized glass surface. Fig. 5 presents the typical spectra of Ty-PDA liposome after polymerization for 5 minutes. The Ty-PDA-liposome-functionalized glass system was immersed into a 1 mM tyrosine solution and the spectral changes were followed spectroscopically for 60 minutes. The intensity of blue PDA at 640 nm decreased, and a broad band between 480 to 550 nm increased, including the tyrosine oxidation product and the red PDA phase.

As colorimetric detection is a versatile inexpensive and portable method because digital photographic imaging. This approach should be exploited to design reliably and robustly attachment of specific biomolecules as the sensing system based on active immobilized Ty. Regulated by the properties of both the functionalized surface and the targeting agent will reach specific targeting relying on lock and key interactions, where the targeting moiety interacts with solely the target. In addition, PDA-liposome functionalized SAM system offers high accessibility of substrate molecules to the immobilized biomolecule and specially, after the recognition event, a small rotation of C-C bond to the polymer backbone occurred. This conformational change disturbed the effective conjugated length and it was transduced through the alkyl chain length. Thus, the Ty-PDA-liposome functionalized glass system is a nanostructured platform upon which a colorimetric sensor, based on tailored surfaces, which were obtained by amino-self-assembled monolayers can be produced. [32]

3.4. Fluorescence emission detection of biological activity by Bt-PEG-fuctionalized glass

The second approach involves the immobilized Bt ligand on the top of SAM glass system interacting with fluorescein

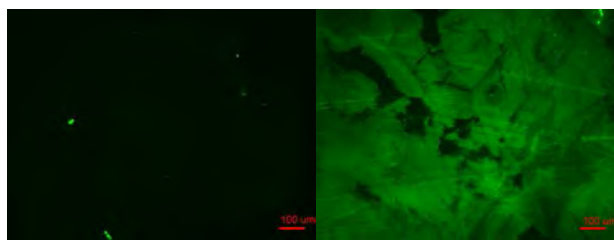


Figure 6. Fluorescence microimage of SAV-Biotin-PG5000-SAM on glass (Right side). Control shows null fluorescence (Left side). Scale bar 100 μ m. Source: The authors.

labeled Streptavidin to demonstrate detection of protein binding. The Fig. 6 shows the fluorescence imaging changing from a not fluorescent structure to a fluorescent attached Bt-SVA on the top of the SAM layer. [34]

CA value of Pegylated-Bt surface was 51°, in contrast to hydrophobic immobilized compounds including stearic acid, paraffin wax, myristoyl alcohol, and cetyl palmitate which exhibits a large hydrophobic contact angle around 110°. [35] The combination of Bt-functionalized glass for targeting the molecule of interest and protein resistance for blocking all other molecules, and high number of EG moieties improves protein repulsion enhancing the mechanical stability of this surface. [36]

The Fig. 6 shows a poor quality of monolayers, which was perturbed by cross-link of head groups Si-O-Si which causes chain distortion and the lack of long range order. [37] The quality of monolayers depends on several factors such as nature and roughness of the substrate, solvent used, temperature, concentration of the adsorbate. [38]

Advantages of this nanostructured bioplatfrom includes a much greater open area enabling a much faster contact of the measured species with optical or luminescent sensor and, thus, a potentially faster measurement; as well as different layer can grow on top of amino-functionalized glass, producing ordered arrangement able to give an optical signal without use expensive instruments as SPR, optical fiber, Raman, or difficult systems as nanofluids or Langmuir films.

4. Conclusion

The characterization and identification of interactions between ligands and biomolecules provides a significant basis for understanding the biological cell. Biomolecular recognition events at solid surfaces demand effective immobilization of biomolecules or ligands. This study used a binding system supported on SAMs, which determines the response of optical biosensor using glass material. It was shown that adsorption from organic solutions on polar solid surfaces can be used to produce a bioplatfrom of homogeneous and compact amino monolayers. The nanostructure liposome was immobilized on the top of the sensing surface as PDA displayed thermochromic behavior after heating, from intensity changes at the 640 nm band, attributed to the blue band formation appeared in the UV-vis spectra and chromic response after an enzyme binding. Furthermore the immobilized Ty enzyme retained its activity, as the sensor showed chromic response in presence of the natural ligand tyrosine. The second immobilization strategy

involved Bt-PEG capable to bridge with fluorescent SVA, which was observed under fluorescence imaging. Both systems, Enzyme-PDA-liposome-functionalized glass offers to recognize natural substrates of immobilized enzyme giving out a colorimetric response; and the Biotin-streptavidin system is accessible to interact with different biotinylated proteins because SAV has four binding sites, facilitating the fluorescence measurement. In addition, SAV can be covalently coupled with different available ligands such as fluorochromes, enzymes and other tethers which make the biotin-streptavidin system widely used in the study of a variety of biological structures and processes. Both sensing mechanism emerges as a promising tools in biosensor development where one of the couple, either the biotin molecule or the colorimetric PDA liposome containing the active enzyme, is immobilized on the transducer element. In addition, Pegylated surface minimizes nonspecific adsorptions, as hydrophobicity increased.

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Statistical metadata in knowledge discovery

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Abstract

Metadata represents the semantic schema of the data collected over the years by an organization in order to apply the business intelligence approach. However, the metadata normally collected are not enough to facilitate knowledge discovery processes because they are conceived, primarily, for the interoperability between information systems. Research undertaken in this study confirmed the need to enrich data warehousing systems with structured meaningful metadata in order to increase the productivity and efficacy of any investigation, including data management and future business analytics. This need led us to adopt and extend the concept of “statistical metadata”. Thus, our proposed conceptual model of statistical metadata not only considers recognized standards, but also represents other additional properties. This means that our conceptual model allows increased levels of detail about the data and quality of the semantic contents.

Keywords: statistical metadata; knowledge discovery; knowledge management; data analytics.

Metadatos estadísticos en el descubrimiento de conocimiento

Resumen

Los metadatos representan el esquema semántico de los datos recolectados a lo largo de los años por una organización para aplicar el enfoque de inteligencia de negocios. Sin embargo, los metadatos normalmente recopilados no son suficientes para facilitar los procesos de descubrimiento de conocimiento porque están concebidos, principalmente, para la interoperabilidad entre sistemas de información. La investigación realizada en este estudio confirmó la necesidad de enriquecer los sistemas de almacenamiento de datos con metadatos significativos y estructurados con el fin de aumentar la productividad y la eficacia de cualquier investigación, incluida la gestión de datos y la analítica futura del negocio. Esta necesidad nos llevó a adoptar y ampliar el concepto de “metadatos estadísticos”. Por lo tanto, nuestro modelo conceptual propuesto de metadatos estadísticos no sólo considera estándares reconocidos, sino que también representa otras propiedades adicionales. Esto significa que nuestro modelo conceptual permite mayores niveles de detalle sobre los datos y la calidad de los contenidos semánticos.

Palabras clave: metadatos estadísticos; descubrimiento de conocimiento; gestión de conocimiento; analítica de datos.

1. Introduction

Recent developments in information technologies, are enabling organizations of all types and sizes to understand and analyse massive amounts of data about their performance and environment. Thus, new management approaches that promote decision-making processes based on data rather than intuition and subjective judgements are becoming more important. The Business Intelligence (BI) approach is a good example of this approach: “BI is a process for analysing data

to help managers and other end users to make decisions that are more informed, based on the use of the information for making decisions with more accurate diagnoses and smarter solutions” [1].

BI technology enables organizations to collect and integrate data, prepare for analysis, run queries against the data, generate reports and create dashboards or other types of data visualizations for supporting decision-making processes. The BI approach can also incorporate forms of advanced analytics (called Business Analytics) such as data

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mining, predictive analytics, text mining, statistical analysis and big data analytics for knowledge discovery. Additionally, Information Management involves not only knowledge generation, but also the use and dissemination of information.

A major component for BI is the data warehouse, which serves as a central repository for all data required for analytics and knowledge discovery. However, the use of data from these repositories is not possible without complete and meaningful metadata.

In the literature, we found different models and standards for metadata specification. According to the European Statistical System [2] the ones which are mainly used by the National Statistical Institutes (NSI) are the Common Warehouse Metamodel (CWM); the Nordic Metamodel; the Generic Statistical Information Model (GSIM); the Data Documentation Initiative (DDI) standard, ISO/IEC 11179 and the Statistical Data and Metadata eXchange (SDMX) standard. Unfortunately, these kinds of models and standards aim to manage the processes between statistical organizations, facilitating the exchange and interoperability between different data sources rather than considering the usefulness of metadata in all phases involved in knowledge discovery and data management. This became evident in a previous study which was concerned with constructing a data warehouse for a research study about innovation in Colombia [3]. We confirmed in that study that conventional metadata are very limited to managing basic information such as data format, type and user privileges. For this reason, conventional metadata cannot ensure the continued viability and usability of data, and unless changes are made, this is likely to be a continuing future issue.

The data for the study of innovation was based on two well-known and recognized Colombian governmental institutions: the Administrative Department of National Statistics (DANE) and from the Administrative Department of Science, Technology and Innovation (COLCIENCIAS). Although these institutions offered some metadata, the amount of available data was limited and not sufficient for our purposes to facilitate the data analysis and the direct access to the data for each member of the research team, (Further collection of information from these bodies would have increased the time and cost of the project)

Further academic research work confirmed the necessity of enriching data warehousing systems with structured meaningful metadata in order to increase the productivity and the efficacy in any investigation, as well as in data management and future business analytics. This necessity led us to adopt and extend the concept of statistical metadata. Thus, our proposed conceptual model of statistical metadata not only considers recognized standards, but also represents other additional properties. Thus, our conceptual model covers increased details and descriptions about semantic contents of data and their quality.

However, the survey and census data were valuable resources not only for governmental departments and academic researchers, but also for the private business sector. These data sets constitute valuable and irreplaceable resources that must be managed in a way that encourages their widest possible usability. In this way, metadata are essential for compensating for the distance in time and space

between the source and the usage of the data [4]. Therefore, all kinds of producers or stewards of data should take into account that data without the appropriate metadata are useless and even harmful in some cases, because of the possible misinterpretation of data. Nevertheless, the need for more comprehensive metadata demands both time and effort, and, the aim of this paper is to propose a new conceptual model which enriches conventional metadata but with minimal relevant elements, moving towards a more simple but complete model, which is much more practical for analysts and decision makers.

In the commercial field, suppliers such as IBM, Informatica and Collibra, which are leading companies according to the latest report of Gartner 2017 [5], address the metadata management through their products which are mainly oriented to data governance. These products provide functionalities for business glossary management. The business glossary is a repository for collecting and sharing the business terms and their meaning in a specific organizational context. The glossary aims to provide a set of definitions of common vocabulary for technical and business users [5,6]. A business glossary generally includes term definitions, term names, term definition examples, term acronyms, term abbreviations, security aspects and compliance restrictions. Furthermore, the business glossary usually has metadata about the data, such as the name (name of the person creating the term definition), the data steward names (assuming there is not just one steward) and the data steward's contact information (phone, email, location) [7]. Nevertheless, the business glossary is usually stored outside the warehouse as the purpose and use is mainly concerned with facilitating communication. In this research, we propose to store administrative and technical metadata together in the data warehouse in order to use them in knowledge discovery phases.

This paper has seven sections. This first section introduces the topic and sets out the aim of our work. The second section, presents a review of literature regarding data warehousing systems and metadata, followed by two case studies which form the third section and confirm the necessity of metadata in knowledge discovery. In the fourth section, we present the materials and methods used in our research work. The results of this work, in the form of the presentation of our new proposal of the conceptual model for statistical metadata, are outlined in section five. In addition, in the sixth section, we present the discussion about our results. Finally, we present the contributions and conclusions.

2. Data warehouse and metadata

A data warehouse is an integrated, time-variant and non-volatile collection of data in support of the decision making process. The distinctive characteristics of a data warehouse is that it contains historical, granular and integrated data, so that various groups of people can examine and analyse the same datasets and achieve a single version of the truth [8].

The data warehouse definition given by Inmon (1991) is valid today, but the data warehousing architecture has evolved to 2.0 version (DW 2.0). According to "DW 2.0 architecture" proposed by Inmon (2008) and "The Data Warehouse Lifecycle Toolkit" by Kimball (2013), metadata are the cornerstones of data warehousing systems. However,

this requirement of metadata contrasts with the fact that many information systems do not implement them at all or do so only partially. With complete metadata, data reusing is much easier and this would help avoid duplicating work in data analytics or research studies which have been undertaken in all types of organizations.

2.1. Metadata

The National Information Standards Organization defines metadata as: “*structured information that describes, explains, locates, or otherwise makes it easier to retrieve, use, or manage an information resource*” [9]. However, the definition which is better known (in metadata) in any area is “*data about data*”, making it more general, independent of context, but rather more ambiguous.

Currently the definition of metadata which has also become popular is that which concerned the organizing of Web resources for facilitating interoperability and integration of resources, in order to provide digital identification and preservation of information. For example, Berners-Lee and the World Wide Web Consortium (W3C) have a more narrow and restrictive metadata definition: “*Metadata is machine understandable information about web resources or other things*” [10].

In this research work, we searched for metadata standards related to data warehousing systems. For this purpose, we mention the Common Warehouse Metamodel (CWM - ISO/IEC 19504) and ISO/IEC 11179 norms (Metadata Registry - MDR). Other contributions are also of relevance, such as the Data Documentation Initiative (DDI) and Metadata Common Vocabulary (MCV). Both of these models are complementary as they work “together” on standards and models already mentioned. However, unfortunately, these proposals also focus on the exchange and interoperability between different data sources. This means that they are restricted on the use of metadata for machines - but not for humans involved in any process of business analytics or knowledge discovery such as data cleansing.

2.2. Statistical metadata

Among the informatics community, the meaning of metadata is usually limited to formal descriptions of how data is typed and formatted with the aim of facilitating the interchange and the interoperability of information systems, as mentioned earlier. Thus, current data warehousing systems only specify some descriptions that are in fact about syntactic properties of data rather than semantic ones.

As conventional metadata do not offer specifics or the context needed to communicate meaning and analyse data, we adopt the term “statistical metadata”. Nevertheless, we found that statistical metadata has focussed only on the official statistics generated by the National Statistical Institutes (NSI) in different countries.

Official statistics have been one of the main areas that have taken on board and recognized the importance of metadata. International organizations such as UNECE, EUROSTAT, OECD have promoted projects that have resulted in new models and standards for statistical metadata,

such as Generic Statistical Information Model (GSIM), Statistical Data and Metadata eXchange (SDMX - ISO 17369:2013), et al. Other proposals have emerged from initiatives by National Statistical Institutes (NSI), such as the Nordic Metamodel. Unfortunately, these contributions are focused on the “metadata on statistics data” generated in NSI, as presented in the Common Metadata Framework [11]. Thus, statistical metadata is defined as “data about statistical data” [12,13].

On the other hand, we agree that statistical metadata is “any information needed by people or systems to make proper and correct use of the real statistical data, in terms of capturing, reading, processing, interpreting, analysing and presenting the information (or any other use)”. In other words, statistical metadata is anything that might influence or control the way in which the information is used by people [14]. In addition we propose, expanding the “*statistical metadata*” beyond the domain of the NSI, so that the metadata is not limited to statistical data, but to any dataset which is of interest of the organization. With this definition in mind, data warehouse designers, managers and data analysts must pay special attention to statistical metadata.

Statistical metadata has two abstraction levels: *microdata* and *macrodata*. Microdata are data about the characteristics of units of a population, such as individuals, households or establishments, collected by census, surveys, or experiments. Macrodata, however, can be defined as data derived from microdata by statistics on groups or aggregates, such as counts, means, or frequencies [13].

Statistical metadata are not limited to the form and contents of data. This kind of metadata also includes administrative facts about data, about ownership responsibility for the initial data collection and the internet access. These administrative metadata are very useful for not only searching and locating of data, but also knowing about their reliability and novelty. However, unfortunately, government official bodies or any kind of open data sites, usually do not offer all the metadata which are needed to fully undertake all the elements of the business analytic processes.

For instance, Fig. 1 shows a snapshot of some metadata for the open data web site: “DATA.GOV.UK – Opening up Government”. A brief description of columns is displayed in the dataset but these columns concern only a few characteristics of administrative data and many of them have unknown values.

3. The role of statistical metadata in knowledge discovery

Before we present the conceptual model of statistical metadata, we must understand why it is necessary to enrich data using statistical metadata. For this purpose, we first present two real cases which highlight some problems that can arise due to the lack of complete metadata.

3.1. Research study 1: Innovation in Colombia

As mentioned in the introduction of this paper, the earlier knowledge discovery project regarding “Innovation in Colombia” was completed during 2009. For that work, we used several “Annual Manufacturing Surveys” provided by

ADDITIONAL INFORMATION	
Added to data.gov.uk	11/12/2011
Theme	Health
Themes (secondary)	Society
Geographic coverage	England
Mandate	No value
Temporal coverage	No value
Schema/Vocabulary	No value
Code list	No value
Service Level	No value

Figure 1. Example of official metadata.
Source: [15]

the Colombian official statistical department DANE and two research databases from the Administrative Department of Science, Technology and Innovation (Colciencias) for building a data warehouse. DANE provided us with an electronic sheet and a short description of columns included in each file, corresponding to a specific year, as metadata. These annexes were crucial because most of the names of columns were numbers which referred to the questions in the surveys. Nevertheless, the researchers needed to look at several digital or paper documents to choose the data properly, which considerably slowed down the analysis of data. If anyone wanted to know, for example, the mean percentage of profits destined for research and development (R&D) of industrial establishments at Medellín city, in a specific year, first it was necessary to identify the annex corresponding to city's codes. After that search, in another electronic sheet, the researcher then needed to search the name of the column that represents R&D variable. Only after these tedious searches, knowing the code for Medellín city and the name for R&D variable, was it possible to return to the survey data for searching for the required value.

We can say that the problem originated by non-mnemonic names is general, and affects both public and private organizations. In addition, it is important that the analysts can have a good quality description of the data for each table or column in order to find the meaning of any variable and other descriptions such as unity of measure, easily and quickly.

On the other hand, inevitably, data structures change over time. This happened to the manufacturing annual surveys. Every year, the DANE department deletes some questions or adds new ones, but we did not have the metadata to allow us to create an integration process using all of the survey results. Additionally, we realized that some concepts such as "small establishment" varies over time and the data producer needed to inform DANE about these changes.

In addition to the above, the conventions used for representing missing values, the format for dates, among other features, delayed the data analysis. In the official surveys used for the "Innovation in Colombia" study, the conventions for missing

values were to assign the number "-99999" but sometimes there were four or six nines. Additionally, these negative numbers affected any numeric calculation. Thus, we needed to "clean up" all the missing values before data analysis, increasing time and efforts.

In addition as well as considering the process of metadata in data integration, there are also essential data cleansing tasks. If the data are not valid, the descriptions nor the inferences made based on them are also likely to be incorrect which could lead to poor decisions that cause loss of time, money and credibility. Data mining has little or no use if applied to data that is of low quality.

Concerning integral data quality, we must consider several dimensions, such as: accuracy, completeness, consistency, and timeliness which are among the most common elements when measuring good quality of information [16]. Mistakes are frequent despite the care in the data capturing by any operational systems and the data produced by official departments. In the manufacturing annual surveys of Colombia, we found all types of errors. Thus, it was necessary to enrich the data warehouse to include the maximum and minimum values that could take each of the attributes of continuous type, in order to know if there were values outside the domain. Similarly, for discrete attributes, we used the set of possible values for checking problems of domain or referential integrity. For instance, we found the number 13 to describe types of legal entity when it was only possible to have 12 different numbers.

Furthermore, when performing data cleansing tasks, we also needed to analyse the outliers in every attribute or variable, in order to determine other possible errors. For instance, the percentage of revenues for investment in R & D values were not outside the domain which indicated erroneous values, but rather the two extreme values of 92% and 87%. These values were typing errors because no Colombian industrial establishment would allocate such a high percentage of sales in R & D. Thus, the importance of the detection of outliers is important as they can have critical effects on data mining, when they are not considered [17].

It is important to know which technique we can choose in almost predictive analysis, for example, whether the distribution of data from a variable has an acceptable fit to some normal distribution. For this, it is necessary to test the normality of data distributions and save the derived values as other relevant characteristics of metadata, specifically as macrodata, to avoid the execution of the same procedures multiple times, for different users. It is also advisable to generate and save, as another metadata, the frequency histogram or box and whisker plots. These are useful descriptive graphs which determine the shape of the distribution of the data for appropriate selection of techniques or algorithms.

For visualization and representation of knowledge, it is also essential to have an explicit statement of metadata, including units of measurement for each variable in any tabular or graphical results produced in a particular analysis. As an example, Table 1 shows the results of a query without human intervention [18]. We can see the great difficulty for understanding the meaning of any variable such as V1612V and its maximum value of 0.92. Instead of using the original short names, the meaning or description for each variable or attribute could automatically replace them by using new data warehousing systems when presenting the results.

Table 1.
Five-number Summary for Selected Variables.

	PEC	V1612V	V1613A01	V1613A02
Minimum value	0	0	0	0
Quartile 1	0	0	0	0
Median	0,03	0	0	0
Quartile 2	0,06	0	0	1
Maximum value	0,76	0,92	12	70

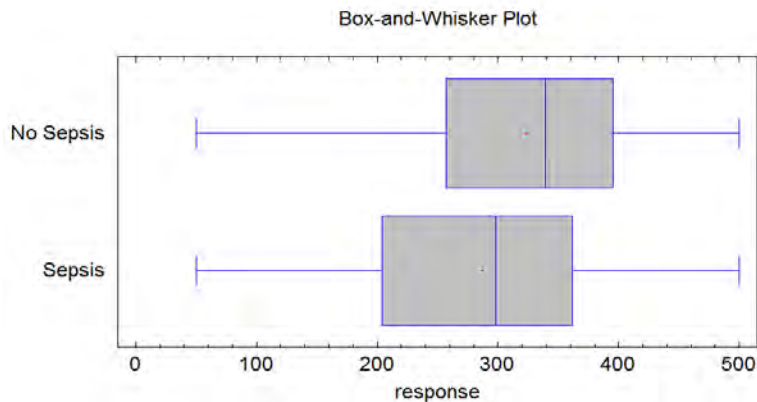
Source: [3]

3.2. Research about sepsis in adult patients

More recently, we have conducted research about Sepsis in adult patients that led us to enrich the conceptual metadata model in order to facilitate the data cleaning process and avoid repeating the same tasks in further analyses. For that research, we designed formats for registering the statistical metadata to discover the data quality and also to ascertain the

Table 2.
Metadata Related to Attributes in Sepsis in Adults Research Project.

Full Name	PaO_2/FiO_2 ratio	Short name	pao2_fio2
Description	Derived from blood pressure (PaO_2) divided by inspired fraction of oxygen (FiO_2). The ratio of <u>partial pressure arterial oxygen</u> and fraction of inspired oxygen, sometimes called the <i>Carrico</i> index. A PaO_2/FiO_2 ratio less than or equal to 200 mmHg is necessary for the diagnosis of <u>acute respiratory distress</u> .		
Source	Patients.xls		
Variable type	Quantitative	Data type	Real positive
Measure unit	mmHg		
Missing values	27 of 589	Median	310
Mean	299	Standard Deviation	108,4
Theoretical minimal value	Unknown	Theoretical maximal value	Unknown
Observed minimal value	50	Observed maximal value	500
Normal Distribution?	Shapiro-Wilk Test (95% confidence) P -value = less than 0, 05. Normality on data is rejected		
Observations	A PaO_2/FiO_2 ratio less than or equal to 333 mmHg is one of the variables in the SMART-COP risk score for intensive respiratory or vasopressor support in community-acquired pneumonia		



Source: [19]

data distribution for selecting the proper techniques required in comparisons. As an example, Table 2 displays the format for documenting each attribute or variable in the dataset. The table includes a boxplot to visually describe the data distribution and detect possible differences in the response variable: the category of adult patients (sepsis and non-sepsis patients) [19].

All the statistical metadata collected for the Sepsis research project such as that presented in Table 2, should be stored as metadata in order to detect changes in variables and to formulate hypothesis about which variables we must consider for deeper analyses. For instance, in the Sepsis database, the variable with short name *pao2_fio2* is the ratio of partial pressure arterial oxygen and fraction of inspired oxygen, sometimes called the Carrico index. According to [20] a PaO_2/FiO_2 ratio less than or equal to 333 mmHg is

one of the variables in the SMART-COP risk score for intensive respiratory or vasopressor support in community-acquired pneumonia. Thus, it is important to know this information to compare the groups in clustering analysis. For example, the distribution of adults who developed sepsis has a lower PaO_2/FiO_2 ratio, as shown in Table 2: The median was 300 mmHg indicating that the 50% of that group had pneumonia. In addition, almost 75% of these patients are at high risk. However, we aimed to validate our findings using a statistical approach and discovered that the Carrico index did not fulfil the normality assumption for the distribution; we needed some non-parametric test to show median differences. Thus, the macrodata included this as part of our results in order that further studies would be able to reduce any unnecessary additional time and effort.

4. Materials and methods

The definition of the conceptual model and its validation constituted an iterative cycle of refinement. The approach chosen in this research for defining the conceptual model was mainly a top-down approach. In this approach, the process started with specifying the global requirements and assuming that each component has global knowledge of the system. We concluded with a model of the solution by enriching the initial model with details.

In the conception of our model, we consider the points of view raised by Grossmann (2002) that indicates that the *“Statistical structures are defined by a number of statistical objects, necessary to model statistical units, populations, statistical variables and statistical data. These objects are defined by their properties, their relations, and the statistical methods which can be applied to such statistical objects in order to produce new statistical objects”* [21].

The conceptual model presented in the next section as a result of our research work is presented using the Unified Modelling Language™ (UML®) Version 2.5 standard [22]. We propose the use of UML because this is an object oriented visual modelling language that has been widely accepted and is easy to understand for users.

The software tool used for drawing the diagram using the UML language was Visual Paradigm Community Edition. This tool supports the latest standards of UML notation.

5. Conceptual model for statistical metadata

The problems outlined in the previous examples forces users to waste efforts that can be avoided if the metadata were available and complete. Perhaps, its importance should be stated more clearly: without metadata, the data is totally meaningless, the content of the information system becomes inaccessible or is of little use [23].

In order to have enough statistical metadata to enrich digital information and create knowledge, we have conceived and designed the conceptual model presented in Fig. 2. This model presents the crucial parts of any data repository. The data source class represents the basic requirements for knowledge discovery. For each instance of data source, such as a text file or some relation in a relational database, is necessary to know some details about its context and keep all administrative metadata for future acquisitions e.g. the format or the URL. Furthermore, to some extent, this administrative metadata also helps to determine the reliability of data.

However, we also know that some data sources are an aggregation of families or groups of variables or attributes. For instance, a survey can have sections to include both demographic aspects and behaviour aspects. Thus, in our conceptual model, a data source can be composed either by a group of variables or directly by individual variables. For each variable of a dataset, is important to collect the full name besides its short name (usually the name in original file) and the other characteristics depicted in Fig 2. The statistics vary depending on the type a variable. Thus, for quantitative variables we propose to store the mean, the median and the mode as estimations of central tendency and the standard

deviation and absolute deviation mean as estimations of the dispersion, as well as the maximum and minimum values. For each categorical variable, it is important to record the mode or modes and the more infrequent values. The diagrams about data summaries are also different for quantitative and qualitative variables and should be stored in the data warehouse as macrodata. This kind of metadata, macrodata, about groups or collections is very useful in data comprehension and the selection of data mining techniques.

The values or measurements for variables like quantities or prices constitute the class of main interest in any analysis. These data are termed as *“Facts”* or *Data Item class* (see Fig. 2). In the case of our research about innovation, for instance, we considered the *Fact Class* has all the quantitative characteristics about industrial establishments such as the quantity of qualified workers and their annual revenues. Any fact table has several dimensions, such as the economic activity and the size of the establishment for our example. These dimensions derive from qualitative variables and are useful for multidimensional analyses. Because data warehouses store historical data, the dimension *Time Class* always appears in the model and we present this dimension as an instance of *Dimension*.

Considering changes can occur in some dimensions, we created the *Validity Period* class in order to register the dates when one instance was valid and the final values before the change. In this way, it will be easier for all organizational members and researchers to consider the correct values for dimensions. In the same way, in order to manage the changes in metadata without significantly affecting the simplicity of the model, we created a relationship between *Validity Period* and the entity *Variable/Attribute*. This relationship is exclusive with respect to the existing link between *Validity Period* and *Dimension* classes, because one change is for one dimension or for some of the statistical metadata, but not for both simultaneously.

In order to create summaries or model fitting it is usually necessary to have different views of data and we therefore suggest a procedure to register the views generated in our conceptual model for metadata as the data source of all the academic production resulting from research works. The reports or models must be related with the techniques or methods used for that purpose. Finally, all the academic production is very useful as future points of reference.

6. Discussion

We present in this document a proposal of metadata which is useful in all the phases of knowledge discovery including data profiling, data analysis and data visualization. This will allow increased understanding and comprehension of the domain and improve communication and comparison of results of future research studies.

We conceived an extension of statistical metadata in a data warehouse applicable to any type of organization, not only for use in official institutions. Descriptive statistics such as minimum, maximum, mean, mode, standard deviation, frequency, aggregates such as count and sum, and additional metadata such as data type, length, discrete values, uniqueness and other restrictions are required for discovering

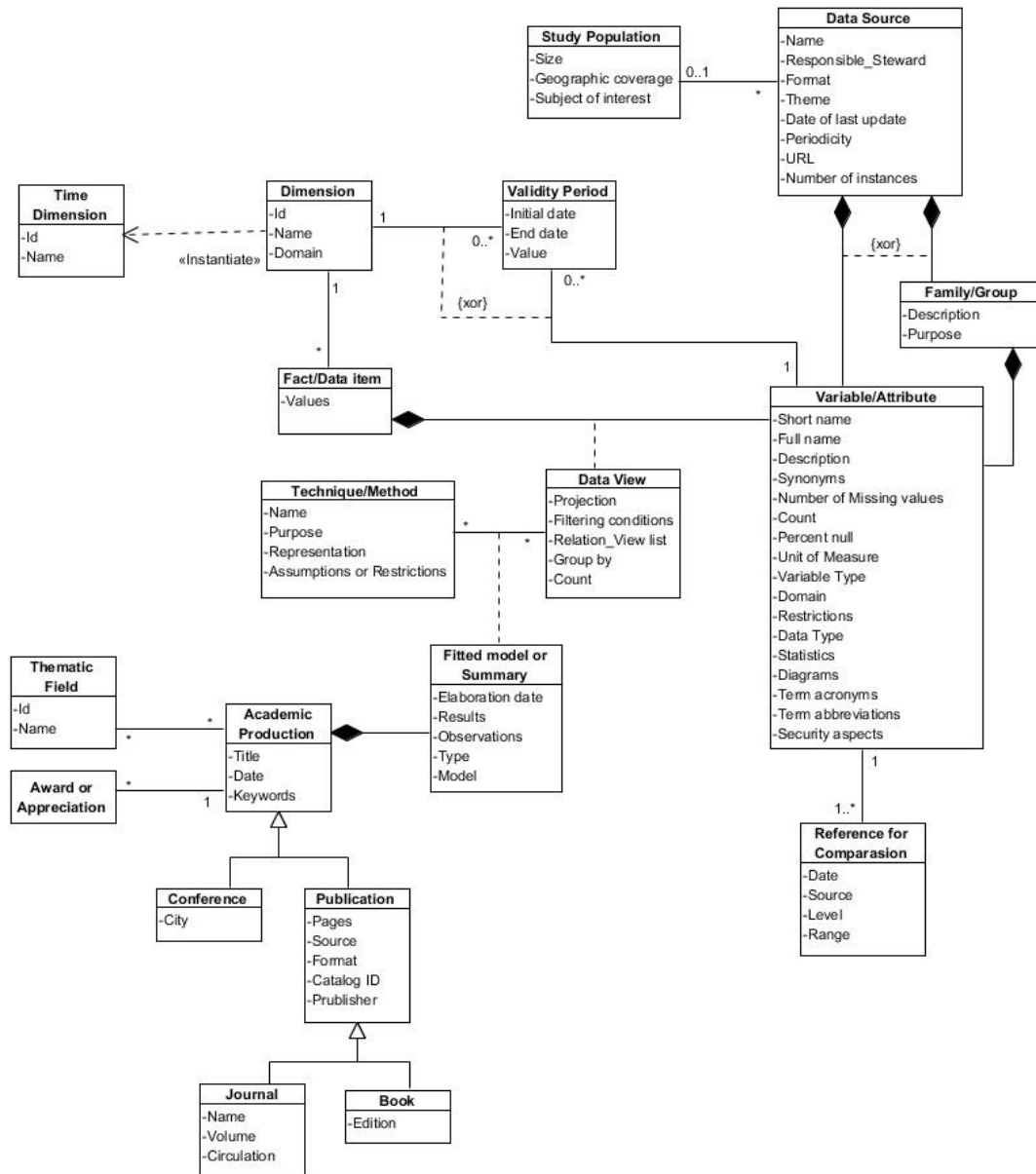


Figure 2. Conceptual model: Collecting data in Data Warehouses; New forms of statistical metadata
Source: The authors

problems such as illegal values, misspellings, missing values, and duplicates in all the contexts. Statistical metadata is vital for the processes of producing and interpreting knowledge. However, defining statistical metadata requires knowledge of the potential users and usages and, thus, this is a complex task. The breadth of meaning is such that the metadata producer must address its production in a manner similar to that used for producing the data itself. Therefore, metadata management must be seen as an integrated part of data production. In addition, as the access of metadata is frequently combined with the data, we propose to structure both of them together in the warehouse.

7. Conclusions

Metadata has several roles to play in addition to the conventional use of interchange and interoperability between information systems. Metadata should provide the basics for data quality validation, data preparation, and for selecting the proper techniques in analytics processes and data comprehension and dissemination. Consequently, metadata should support any knowledge discovery in databases and analysts should use them in order to be increase the efficiency and effectiveness of business processes.

We adopt and generalize the term statistical metadata to

emphasize the necessity to design and represent administrative metadata, microdata as well as macrodata with the aim to have an explicit and complete statement of the information in any data warehouse. Administrative metadata are necessary because currently the data in a data warehouse arises from multiple sources and these sources not only are relevant for future acquisitions, but they also determine in part the data quality. In this way, we propose an enrichment of metadata, specifically in macrodata, in order to improve the accessibility, generation and dissemination of current and future research.

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Class A prediction of a retaining structure made by a pile curtain wall executed on a tropical soil

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Abstract

Some retaining structures can be designed on a temporary basis, in accordance to the geotechnical design and a predefined construction plan. Of course this may not be valid elsewhere, but in Brasília, where residual and laterized soils do prevail, best mechanical resistances are obtained in the porous clay strata along the dry season. That means, it is controlled by soil's suction, i.e. soil behavior presents a dependency on the unsaturated response of the medium. In numerical terms, to predict the soil-structure behavior it is necessary to include the atmosphere-soil interaction in the computational tool, using a hypoplastic model. The paper thus details on this aspect and on the numerical simulations of an existing retaining structure founded in the tropical soil of Brasília. The structure was monitored in terms of displacement, along local dry and wet seasons, and was simulated by a constitutive law calibrated by means of unsaturated laboratory tests.

Keywords: unsaturated response; numerical prediction; hypoplasticity; retaining structures; pile curtain.

Predicción clase A de una estructura de contención en pilotes ejecutada en suelo tropical

Resumen

Algunas estructuras de contención de acuerdo con su diseño geotécnico y plan de construcción predefinido. Por supuesto, esto no extrapolable a todos los sitios de análisis, sin embargo, en Brasília, donde predominan los suelos residuales y laterizados, se obtienen las mejores resistencias mecánicas en los estratos porosos durante la estación seca. Esto significa que es controlada por la succión del suelo, es decir, el comportamiento del material presenta una dependencia de la respuesta no saturada del medio. En términos numéricos, para predecir el comportamiento suelo-estructura fue necesario incluir la interacción atmósfera-suelo en una herramienta computacional, utilizando un modelo hipoplástico. El trabajo detalla de esta manera las simulaciones numéricas de una estructura de retención fundada en el suelo tropical de Brasília. La estructura fue monitoreada en términos de desplazamiento, a lo largo de las estaciones locales secas y húmedas, y fue simulada por una ley constitutiva calibrada mediante pruebas de laboratorio no saturadas.

Palabras clave: respuesta no saturada; predicción numérica; hipoplasticidad; estructuras de contención; pilotes tangentes.

1. Introduction

In recent decades, the numerical models had a very important evolution from the point of view of prediction tools for the behavior of geotechnical structures. However, most of the analyses are still evaluated on qualitative rather than quantitative manner, as several external (and unknown) factors can directly

affect the results, turning it difficult to consider all physical factors into simulations. Indeed, for non-classical soils behavior, a high dispersion of the data tends to be achieved when cross comparing numerical predictions with experimental in situ results [1].

Therefore, one of the main objectives that geotechnical engineers want to achieve is the prediction or validation of real case problems in full-scale dimension. That's why the usage of numerical modelling techniques has become so

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Figure 1. Overall situation of the excavation work in the city of Brasília
Source: Taken of google maps.

increasingly important geotechnical researchers, albeit it is quite a challenging task. A good simulation depends on many aspects that affect the problem, among them the numerical model and input parameters, the correct execution sequence and other variables to properly address the geotechnical case under consideration [2]. As it will be exposed in this paper, traditional theories may eventually have disadvantages to perform analyses that properly predict the behavior of a geotechnical structure, especially when the soil is unsaturated or has distinctive features as structure degradation, cementation, and so on. Therefore, a hypoplastic constitutive model for clays that reproduces the unsaturated soil response of the material [3] is adopted herein. The final objective is the simulation of deep excavations made of anchored pile curtains in the tropical soil of Brasília, a soil that do conform to typical formations found in the Brazilian Midwest deposits.

2. Site Analysis

The construction site in question was an excavation executed at the hotel sector of Brasília, where a business related commercial building (Fusion Plaza) was to be built (Fig.1). In this site, by means of geotechnical investigations, it was possible to identify two main geotechnical strata (Fig.2). The first layer of 11 m o thickness approximately is composed by the typical red “porous collapsible” clay of the Federal District, geotechnically described as a clay with contents of sand, silt and gravels, soft to medium consistency. Beneath this overburden layer lies a clayey silt with sand lens (saprolitic soil), with medium to stiff consistency. The designed retaining structure (in the analyzed section) consisted of an evenly spaced 60 cm diameter “pile curtain” with total free + embedment length of 18 m spaced 1 diameter center to center apart. The embedment length was 5 m with several levels of anchored beams holding back the structure, tied to the ground by “passive” anchors that have been built using the standard execution technique of soil nails [4,5]. A typical cross section is sketched later in this paper.

In the localized area of the excavation (Fig. 2), in the

upper strata, it was possible to observe the typical mechanical characteristics of this subsoil already seen elsewhere in Brasília, i.e. a very low strength to penetration in the SPT test (varying of 1 to 6 blows), a low bearing support, and an unsaturated region with high porosity, low density and relatively high permeability which overall details are found elsewhere [6,7,8,9]. Due to tropical laterization and lixiviation processes that this material has undergone, it presents a quite unstable open structure that “collapses” (sudden decrease of volume) when simultaneously subjected to wetting and loading [10]. Another research on a nearby site [11] has also demonstrated that the superficial weak strata varied up to 7 m in depth in 62 SPT borings. A highly-weathered material with oxides and lateritic concretions, that would justify the weak bonding between minerals, was also found by this latter author. The underneath saprolitic layer possibly comes from the weathering of the local mother rock, a metamorphic slate typical from all the region.

2.1. Basic characterization of the material

A complete characterization of the material was done in terms of physical and chemical tests. Table 1 shows some of the basic properties and geotechnical parameters of one sample of soil along the studied curtain section, where it could be possible to assess the correspondence between these values and those already published from the typical laterized “porous” clay of Brasília (see for instance [6,9,10,11])

In Fig. 3, some particle size distribution curves are shown for three distinct depths, denoting that perceptible differences in results are found when the tests are carried out with, or without, any dispersing agent to “break down” cementing bonds on the particles. As already noticed before for this material [10], the granulometry changes given the existence of “lumps” of bonded particles made of clay and silt minerals, forming false large particles that are interpreted as sand grains when analyzing the soil without the dispersing agent. There is a clear distribution of macro and micropores (bimodal) on the tested sample, despite of the granulometric curve being unimodal in both cases. Moreover, [12] inferred

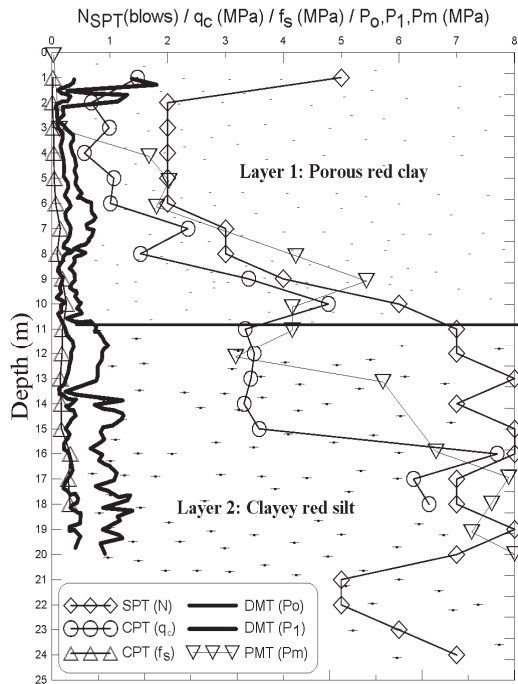


Figure 2. Results of several in situ tests in site under study
Source: The Authors

Table 1.

Basic characterization of the material under analysis

Sample	1B	2A
Depth (m)	6,0	9,0
w (%)	26,8	19,6
γ_s [kN/m ³]	28,01	28,02
γ_d [kN/m ³]	11,39	12,88
γ [kN/m ³]	14,70	15,51
Gs	2,81	2,82
LL (%)	48	50
PL (%)	29	30
PI (%)	19	20
IC	1,13	1,55

Source: Modified of Ruge *et al.* [4]

that the soil of the Brasilia-DF is composed by microconcretions of clay shaped by grains of silt and sand, producing an internal porous structure, that tends to “collapse” under a simultaneous load and wetting stage.

2.2. Microstructural analysis of the material

A mercury intrusion porosimetry test was also carried out with undisturbed samples from the site. It allowed the determination of the natural size and distribution of pores of the system (soil), as well as the bulk density and packaging density of a porous media core. This process is based in the

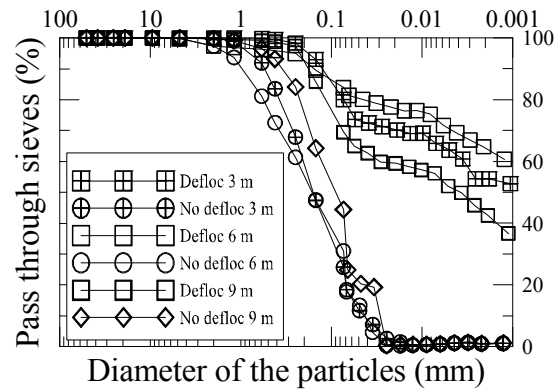


Figure 3. Particle size distribution at the samples
Source: The Authors

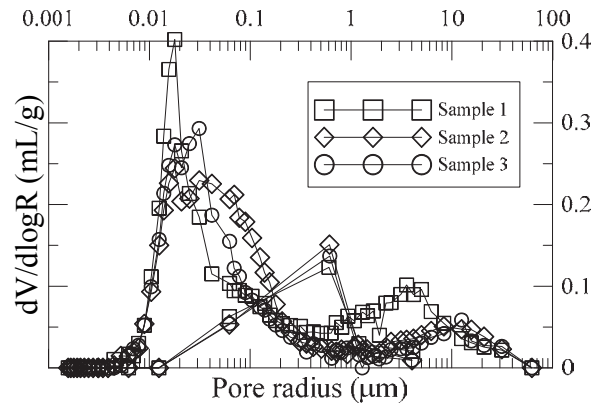


Figure 4. PSD of different samples at 9m of depth
Source: The Authors

injection of mercury within the pores of the sample, in order to estimate its capillary pressures. As a general rule, the size of the pore inversely proportional to the applied pressure. Hence, the tests allowed the determination of the pore's volume and the distribution of size (PSD-Pore Size Distribution) (Fig.4). It is important to note in this former figure, where the derivative of the accumulated pore volume vs. pore radius is plotted against radius, that the variations of the inflexion points (in the source graph) are reflected in Fig. 4 by peaks related to the existence of micro and macropores. In the present case, the results evidenced a predominance of micropores in the studied sample.

Fig. 5 depicts a 15000x image of the SEM test, evidencing the lumps of clay of the sample, and the related macropores. It shows such lumps as aggregations that behave as cementing agents around of the minerals. In some cases, the soil's minerals form links between two or more aggregations. It can also be noticed from this image that the water and the bonding aggregations can be located in three kinds of pores: macropores, mesopores and micropores. The macropores have diameters higher than 50 microns. The mesopores have dimensions between 50 and 2 microns, and the micropores less than 2 microns [13]. In this particular image of 15000x, the micropores are revealed and can even be measured with diameters between 200 nm and 800 nm (see Fig. 5).

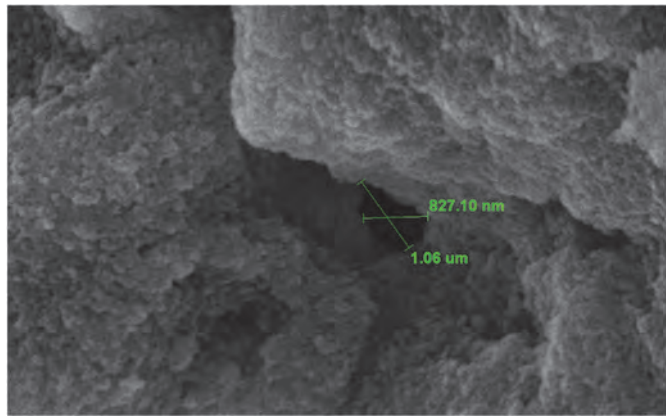


Figure 5 SEM image for 15000x in sample to 3 m of depth
Source: The Author

By adopting the combined data and results from both the porosimetry and the retention curve tests, one can effectively conclude that the macropores, the mesopores and the micropores have an important relevance in the mechanical and hydraulic behavior of this particular tropical material. Therefore, it is clear that the entrapped water from the macropores can be eventually mobilized to easily flow within the structure of the material, as infiltration water, thus directly affecting the variation of suction on this soil profile. Within the meso and micropores the water is more difficult to be mobilized as it is retained by other physical forces, thus helping to preserve the natural saturation of the soil. This tendency of having double porosity may show a distinct behavior of the soil's stored water during the buildup of pore pressures that can take place during the load process. This is so because the small pores (micro and mesopores) will probably continue to drain the excess of pore pressure long afterwards the bigger pores (macropores).

The water that is stored in the micropores (adsorbed) is difficult to remove due to electrochemical attraction between anions of the water elements and the cations of the clayey particles. Thus, the cementing mineral aggregates that are possibly located in the skeleton of the material can be founded in the percolation water. It is clear the cementation in soils like the one under study has been well developed, originated from pedogenetic and lixiviation (combined) effects on minerals with carbonates and oxides, typical from climatic conditions of tropical regions [13].

The presence of different cementing minerals can increase an elastoplastic response in the soil. This effect is evident as a phenomenon known as collapse, previously cited, allowing the existence of plastic strains, due to the fragile nature of the cementing bonds. An important factor that defines the hydraulic and mechanical behavior of the porous clay is the fact that metastability and partial saturation provide similar effects. Therefore, the numerical modelling of this soil using a physical-mathematical model is a complicated task. The suction effect also influences in the hardening of the non-soluble cementing minerals [14]. For that reason, only in a saturated stage, where the suction is nonexistent, can one assume that the real cementation and the non-soluble minerals do act in a separate manner.

2.3. Mineralogical and chemical characterization

The X-ray diffractometry (XRD), which is a valuable tool to the mineralogical characterization of clayey minerals and other components, was also employed with the retrieved samples. The tests were carried out for samples at 6 m and 9 m deep. Using these technique, it was possible to identify minerals as quartz (63%), kaolinite (21%), gibbsite (11%) and hematite (5%), which goes along with results reported by [15]. In addition, it shall be highlighted that, although the quantity of these minerals is relatively low, their presence can have an influence on the cementation of the clay particles, probably generating a metastable behavior on the whole structure as suggested by [16]. Besides, collapsible soils form part of a metastable soil group, where the initial structure is broken due to environmental variations, in agreement with [17]. This latter author has also defined collapsible soils as the entire lateritic porous surface, characterized by the partial saturation and bonding.

2.4. Unsaturated and saturated laboratory experiments

2.4.1. Strength and consolidation tests

Fig. 6 shows the results of oedometric tests with 9 m deep samples at saturated, unsaturated and reconstituted conditions.

In the saturated curve, it is possible to confirm the response from a partially structured soil, where the bonding has an influence on the derived strains of the sample (at natural fabric conditions). It is readily shown that the Brasília clay presents a metastable structure in the $\ln p$ vs e space,

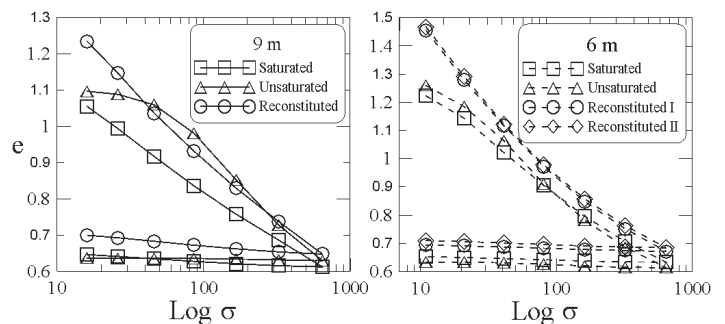


Figure 6. Oedometric test of Brasília porous clay
Source: The Authors

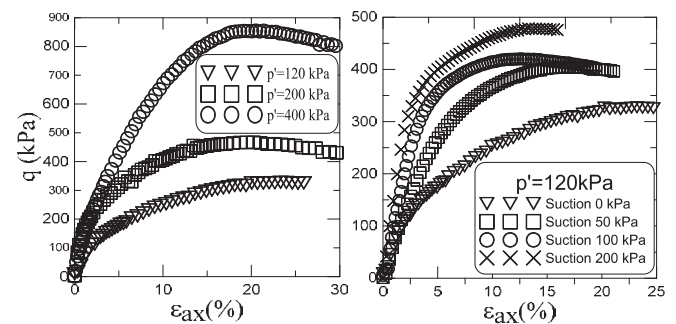


Figure 7. Triaxial test of Brasília porous clay
Source: Modified from Ruge *et al.* [4].

where the stress sensitivity decreases along the loading stages, a characteristic response of normally to lightly overconsolidated clay materials. In relation to drained triaxial tests with samples under both saturated and unsaturated conditions, as presented in Fig. 7 (a, b), it is possible to visualize responses for respectively distinct (increasing) confining stress and suction levels.

2.4.2. Soil Water Retention Curve

The relation between suction and humidity represents an important function in the characterization of an unsaturated soil, this relation can be evidenced by means of the comparison between the stored water and the soil suction, usually denominated as the “suction water characteristic curve” or SWCC. Fig. 8 shows the SWCC of the soil through the axis translation technique, with a maximum matrix suction of 1500-kPa that corresponds to a 35% of residual volumetric wet content, according to the distribution of pores and the retained water. The mathematic model proposed by [18] by means of the eq. (2) was then selected to simulate the behavior of the SWCC in the material. This model simply relates the saturation degree with the pressure head.

$$S(\phi_p) = S_{res} + (S_{sat} + S_{res}) \left[1 + (g_a |\phi_p|^{g_n}) \right]^{g_c} \quad (2)$$

3. Instrumentation of the excavation

Three lines of (passive anchor) nailings of respectively 17, 12 and again 12 m composed the typical supporting device of the excavation/retaining structure. In the selected section for instrumentation, it was installed an inclinometer unit that was located one meter behind the equally spaced piled structure. This was done in order to monitor the deformations in this structure during the different stages (or execution events) of this particular excavation/wall development (Fig. 10). They were pinned to the piled curtain through anchored beams at distinct depth levels (V1, V2 and V3).

The execution procedure was quite straight forward. The piles were firstly executed and excavation was proceeded until each of the anchored beams. The nails were inserted and the beams were subsequently constructed and attached with

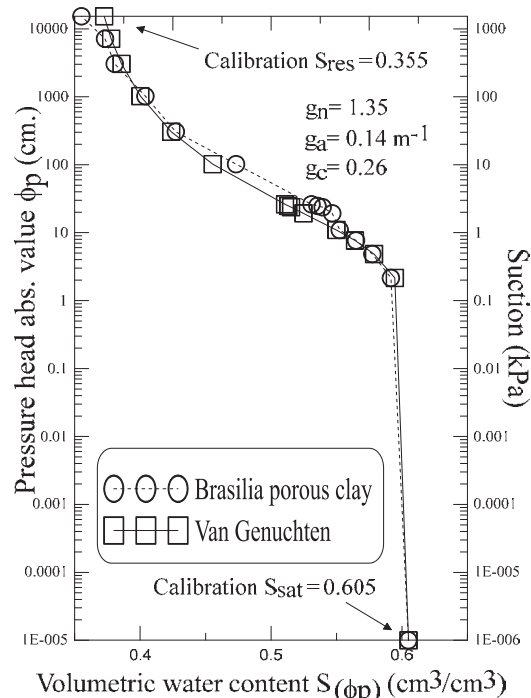


Figure 8. SWCC of the Brasilia porous clay.
Source: The Authors

bended bars to the recently executed nails (the whole process in sequence, at each excavation level). Inclinometry and horizontal displacements were taken throughout this sequential series of events, and afterwards (see timeline in Fig. 9).

3.1. Inclinometer measurements

Fig. 15 presents the inclinometer results sorted for time in days, where the maximum displacement of 24,00 mm was measured in a date very close the end of the 13-m excavation depth below ground level (at 115 days since beginning). It is also noticeable the low level of horizontal displacement of around 2,5 mm that was measured just after the first excavation sequence (up to V1 – 8 days’ value), before the installation of the nail.

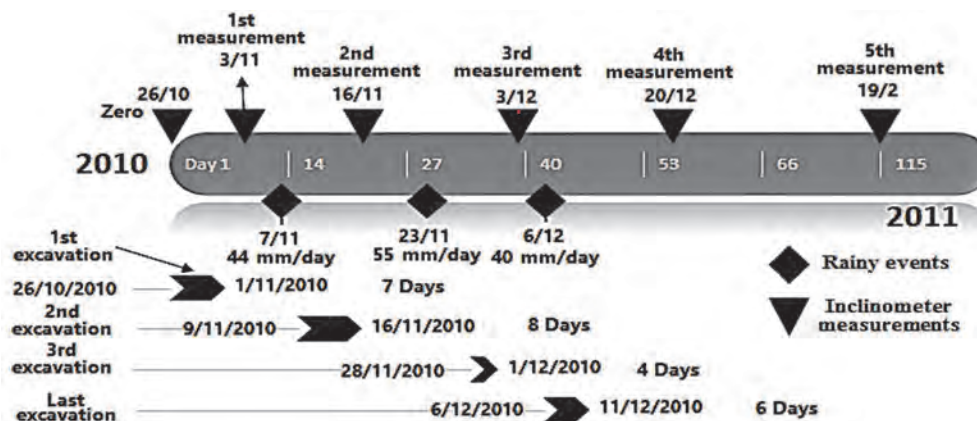


Figure 9. Timeline of the excavation under analysis
Source: The Authors

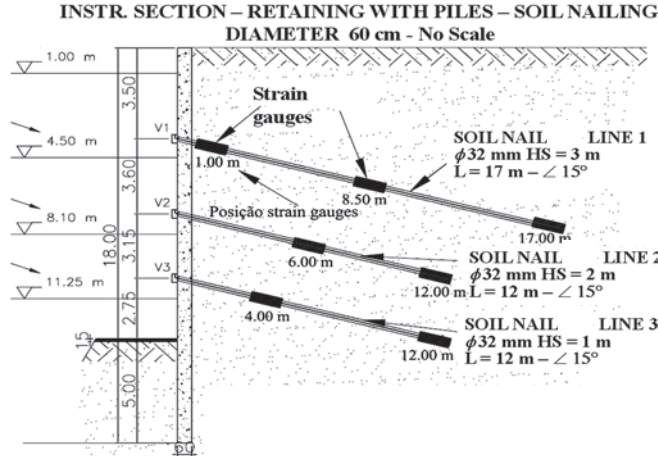


Figure 10. Typical section of the excavation
Source: The Authors

A total displacement of around 4 mm was measured just after the second level of excavation (up to V2 – 21 days' value), where the first upper level of nail was already in place. Between the 21th and 37th day occurred the maximum rainy events on the site, which caused a significance difference among the measurements observed in the Fig. 16. Also, this situation can be analyzed in the timeline shown in the Fig. 9. From the 37th. day until the 55th. (last excavation) the same pattern of behavior was noticed for the measured displacements along depth, with a maximum value of around 22.00 mm. Surely, the observed behavior was simultaneously affected by the excavation sequence and the presence of strong and continuous rains in the region. However, at such time there was a rain event of relatively strong magnitude, that a priori does not seem to have significantly affected the measured displacements, given the fact that dry weather prevailed during all remaining excavation period

4. Constitutive model and parameters calibration

4.1. Reference model

This research adopted as reference model the hypoplasticity theory for unsaturated soils. It also used constitutive equations that were developed with the critical state concept and effective stress principle, considering the effect of an increasing stiffness that was governed by the variation of suction on the mechanical response. The phenomenon of collapse by wetting [3] was also considered.

4.1.1. Constant suction model

As previously mentioned the reference model is supported by the concept proposed by [3]. In this case, suction influences both effective tension and normal forces on the interparticle contacts, hence improving the stiffness of the soil's skeleton, as the particles are closer and interact on a rather stronger manner. In other words, this behavior expands the State Boundary Surface (SBS), likewise bonded soil particles within cemented saturated geomaterials [19].

Under such conditions, the SBS size for unsaturated soils is defined by the NCL, which on the other hand is based on the compression law given by [20] for the critical state line, as described in the following equation:

$$\ln(1+e) = N(s) - \lambda^*(s) \ln\left(\frac{p}{p_e}\right) \quad (3)$$

From where e is the void ratio, considered as a state variable in the constitutive model. The expressions $N(s)$ and $\lambda^*(s)$ predict the position of the inclination of the compression virgin line in the space $\ln(p/p_r)$ vs $\ln(1+e)$ for a particular suction s . Equation 4 shows the expression for an equivalent Hvorslev type tension on the NCL at a given suction s [21].

$$p_e = p_r \cdot e^{\left[\frac{N(s) - \ln(1+e)}{\lambda^*(s)} \right]} \quad (4)$$

[22] modified the values of the barotropy f_s and picnotropy f_d , since it was demonstrated that the incorporation of the virgin compressibility in the intercept $N(s)$ affects the original values proposed by [23]. It is important to consider that the reference model describes the behaviour of the material for any state of overconsolidation. Therefore, some few extra assumptions need to be formulated in order to define the constitutive equation (eq. 5) at any stress state, as follows: (1) the stability of the interparticle contacts is governed by the suction level; (2) in more open soil structures the coordination number tends to be lower, hence the contacts support larger shear forces [3]. Therefore:

$$\dot{T} = f_s(L:D + f_d N \|D\|) + f_u H \quad (5)$$

Where s was introduced to consider the first assumption, and f_u is the modified picnotropy factor that controls the tendency of the soil's structure to collapse, as reproduced by the second assumption. When the latter factor is equal to 1 in the SBS, the structure tends to be as open as possible, and collapse is solely controlled by the H variable. Instead when f_u tends to zero, $OCR = p_e/p$ tends to infinite, hence no wetting induced interparticle slippage occurs in a highly overconsolidated soil.

$$f_u = \left(\frac{p}{p_{SBS}} \right)^m \quad (6)$$

Where p^{SBS} is the effective mean stress at the SBS, that corresponds to the current normalized stress T/trT and the current void ratio e . The variable m is a model related parameter that controls the influence of overconsolidation on the wetting-induced collapse. It shall be pointed out that the model for the unsaturated response of the soil do contain some saturated related parameters (ϕ_c ; N ; λ ; κ ; r), according to [24]. Besides, variables N ; λ ; κ are calibrated based in a simple isotropic loading and unloading experimental test. These parameters must also be calibrated with basis on the inclination of the isotropic unloading line (details in [22] and Fig.11).

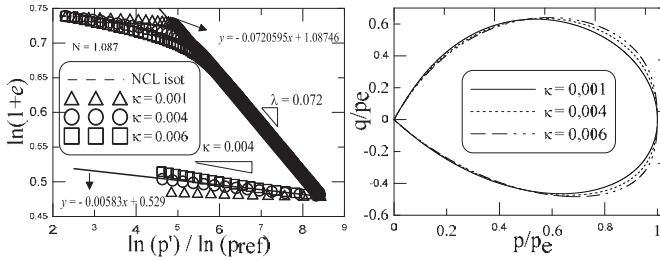


Figure 11. Definition of parameters N , λ^* , κ^* and quantities p_{cr} , p_{cr}^*
Source: The Authors

The critical state friction angle (ϕ_c) is found by using a linear regression with the points of the critical state line, which is derived by available experimental shear tests. The parameter r must be evaluated directly with the ratio of the bulk and shear moduli, which are obtained with the compressed normally stress state line from such tests. Since the model predicts a gradual degradation of the shear stiffness, it is advisable to find an appropriate value of its parameters by using a parametric study. The extension of the proposed model will require to take on account the influence of the suction variable on both N and λ values, respectively denominated as $N(s)$ and $\lambda(s)$. m controls the collapse of the structure along the wetting paths. S_e is the value of suction in the entry and/or exit of the air pores. The scalar quantities n and l are included in the formulation of $N(s)$ and $\lambda(s)$, so to control the unsaturated NCL.

4.2. Calibration of the parameters

It is necessary to adjust the parameters obtained at the laboratory through the constitutive law selected for the numerical phase. The calibration of the saturated parameters (λ^* , κ^* and N) are shown in Fig. 11. The friction angle of the critical state is obtained (ϕ_c) from results in triaxial tests. The unsaturated parameters m , l and n of the model can be computed from the saturated and unsaturated normal compression lines, using isotropic compression tests and eq. 7.

The parameter m is presented in Fig. 12. It is possible to analyze the saturated and unsaturated NCL and to obtain the value of $N(s) = 1,14$. From the equation of NCL_{unsat} (Eq. 7), can also found the value of $n = 0,032$ by solving for $s = 200$ kPa and $S_e = 39$ kPa (from the SWCC). Since both κ and $\kappa(s)$ values are equal, as depicted in Fig. 12, the parameter l takes the value of zero.

$$N(s) = N + n \ln\left(\frac{s}{S_e}\right) \quad (7)$$

5. Computational model

As previously cited, a large excavation pit for a commercial building was constructed in the North Hotel Sector of Brasilia. The pit was around 13-m deep by +100 m wide in a rectangular format (see Fig. 1). A contiguous spaced pile curtain wall was constructed using 60 cm diameter bored piles 1 diameter apart. This wall was designed to be temporarily sustained by three levels of passive anchors

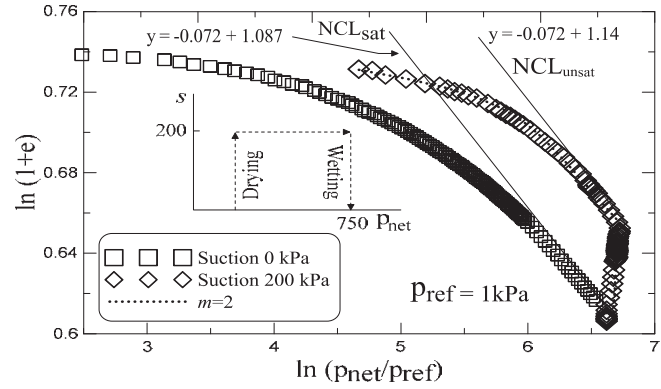


Figure 12. Calibration of the parameter m .
Source: The authors

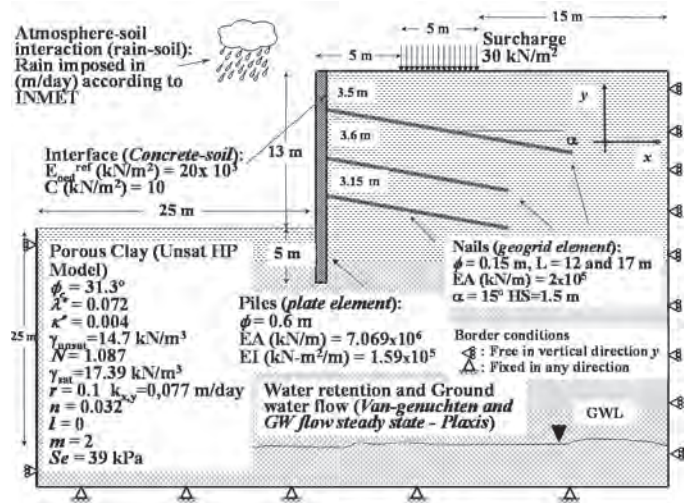


Figure 13. Computational model of the geotechnical problem. The excavation sequence is reproduced by the time line history of Fig. 9.
Source: The authors

(nails) and beams, as represented in Fig. 10 – later to be held in place with the structural slabs of the edification. The subsoil consisted of a homogeneous layer of the typical unsaturated Brasilia porous clay, with a natural specific weight of around 14,70-kN/m³. Other parameters were duly estimated via laboratory results or local experience, as depicted in Fig. 13.

Table 2 complements de previous cited figure, where it is possible to observe the properties of the some of the variables

Table 2.
Elements in the computational model

Curtain of contiguous pile	
Material behaviour	Elastic
Axial Stiffness EA [kN/m]	7,069 x 10 ⁶
Flexural Stiffness EI [kN/m²/m]	1,59x10 ⁶
Weight [kN/m/m]	6,78
Poisson ratio	0,15
d [m]	0,52
Soil nailing (geogrid element)	
Axial Stiffness EA [kN/m]	2 x 105

Source: The authors

Table 3.
Numerical sequences in the excavation process

Stage	Description	Average rain (mm/day)	Duration (days)
1	Geostatic stress balance	1,70	-----
2	Pile borehole and surcharge	1,70	2
3	First excavation - 4.50 m.	8,30	5
4	1st row of nails	12,60	6
5	Second excavation - 8.10 m	3,90	7
6	2nd row of nails	7,03	12
7	Third excavation - 11,25 m	21,63	3
8	3rd row of nails	21,13	3
9	Final excavation - 13.00 m	10,06	5

Source: The authors

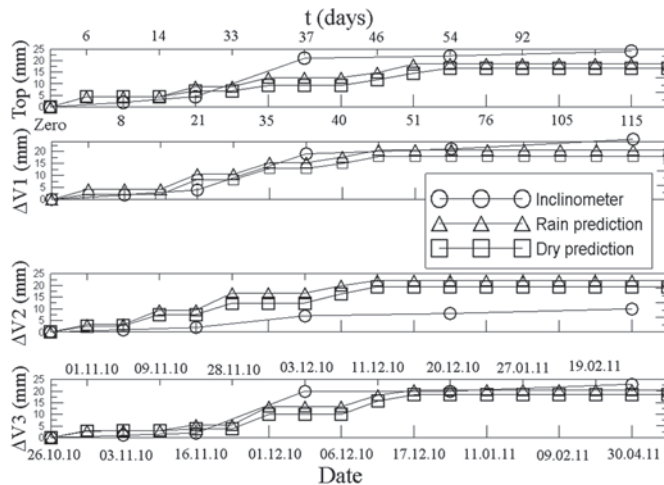


Figure 14. Numerical predictions according to depth of the soil nailings
Source: The Authors

from the proposed model for the numerical analysis. It shall be noticed that the pile wall was introduced as an equivalent plate element with thickness d but similar flexural rigidity, as a 2D modelling was adopted rather than the more realistic 3D case.

One shall realize, on the other hand, that besides of the constraints of the bi-dimensional analysis, it was possible to include the “environmental factor” (rain simulation) in the simulations, for each constructive excavation sequence, as stated in Table 3.

Among the objectives, it was tried out the comparison between simulated and “real” (inclinometer related) horizontal displacements along the wall. The simulations took into consideration both the rain and execution events (Table 3), and a hypoplastic model [3]. The horizontal measurements were made by a total station device and brass pins on top of the piles, as well as on top of each of the anchored beams. Fig. 14 depicts the evolution of displacements along with the execution sequence (in days from time zero – first reading before excavation – see Fig. 9). The predictions included the measured rain from the period and a non-realistic “dry” scenario, just to contrast the results from the constitutive model, i.e., to check upon the sensibility of considering or not suction variations into the soil.

Table 4.
Predictions of geotechnical structures

Prediction	Moment	Results
A	Before event	-----
B	During the event	Unknown
B1	After event	Known
C	After event	Known
C1	After event	Known

Source: Lambe [23]

6. Numerical predictions using the hypoplastic model with an unsaturated response

Given the fact that the numerical analyses consisted of 2D simulations of aforementioned geotechnical problem *before* the real excavation process took place, one can conclude that “type A” predictions in accordance to [25] (Table 4) were actually carried out in the present research.

Plane strain conditions were considered to represent the problem, and the wall geometry and surrounding elements were modeled with 1682 finite elements of 15 nodes. The piles (or equivalent plate) were simulated using appropriate values of flexure and axial stiffness, as shown before. Interface elements were also placed around the plate’s boundary so to adequately reproduce the pile-soil interaction slippery effect.

As previously commented, the excavation sequence was simulated in numerical stages that tried as faithfully as possible to reproduce the real sequence in situ. Atmospheric conditions that may also influence the soil suction and overall behavior of the structure were considered “as close” as possible to real (regional) measurements of pluviosity and weather. For instance, it was introduced a rain value in [m/day] along the analyses, based on the instrumented data. Given the specific characteristics of this soil in terms of mineralogy, structure, depositional aspects and geotechnical behavior, and the intrinsic aspects of the site and work (execution sequences and timing, rain events and so on), a fully drained condition was envisaged and hence adopted.

Although not explicitly commented before, one of the final aim of this exercise was to develop and validate research tools to properly simulate, by means of traditional FEM analyses, a real geotechnical structure of the region. This structure, as usually done in the region, was constructed under unsaturated tropical soil conditions, as well as variable rain fronts (soil humidity events). An important issue was the possibility of developing a temporal evaluation of the execution that included “real” precipitation stages. As it will be demonstrated soon in this paper, the increased complexity of the numerical model has indeed paid off in terms of accuracy of results. It shall also be emphasized that, in this type of validation, the qualitative tendency is also of importance, as the site behavior do suffer from many external factors that cannot be completely inserted into the numerical model – hence accounts for simplifications must always be done [1].

6.1. Deformations in the curtain

Fig. 15 presents the measured displacements and the predictions over time for the top of the pile and the distinct

levels of the beams in the wall. The predictions are tied to similar dates (in days) to the execution sequence, so to get comparable forecasts on the analysed problem. HP stands for the predicted horizontal values, whereas Inc relates to the measured inclinometer values. It can be initially noticed in this graph the expansion of the displacement level from day 21 to 37 (more pronounced in the measured data rather than in the predicted one). Indeed, this period coincides with the third stage of the excavation, where high rates of rain with values close to 50 mm/day took place. This is considered as heavy rain event, since in Brasilia most of the events last short time spans, sometimes of 50 (+) mm in less than 60 minutes [26].

It is also significant to note that the typical Brasilia soil material have permeabilities that are relatively high, in the range of 9×10^{-5} cm/s (so similar to fine sand, given the porous structure at the top surface layers). Therefore, heavy rain effects may eventually increase rapidly the humidity at the surface levels, especially during the continuous rainy season (that goes from around November to April depending on Pacific conditions – “el niño” or “la niña” effects). This effect will change suction values along depth, consequently the behaviour of the structure and may cause a high impact in the suction when the saturation increases. This is revealed in Fig. 15, where one notices the continuous increase of displacement measurements from day 37 and beyond (day 37 relates to the beginning of December).

Nevertheless, rains of short duration on a high temperature environment (annual average above 20-mm), typical of Brasilia, can also cause a fast evaporation of the

water that eventually runs off to surface or percolates into the soil. Probably the downwards wetting front from rainy events will solely affect the soil's suction at the shallowest depths of the deposit.

7. Conclusions

In this research, it was possible to confirm the presence of macropores and micropores in the soil structure with the use of porosimetry results and SEM observations. This distinct presence and variability will undoubtedly affect the mobility and retention of water in the soil – hence changing its behaviour under shear or loading conditions, as it was demonstrated herein.

This is so especially for particular “tropicalized”, laterized and unsaturated soils as the Brasilia porous clay, where the influence of the water content, hence soil's suction on the overall macro behaviour, is real. Matric suction also influences the mechanical properties of the deposit, which leads to the initial conclusion that numerical analyses of such geotechnical media and buried structures must take on account, somehow, this effect on the rheological model. Experimental as well as numerical (forecast) results did demonstrate the clear necessity to include the suction phenomena within the hypoplastic model, leading to distinct results (or forecasts) in accordance to the input rain throughout the study period of the site/structure. The problem however is not so simple as it seemed at first view.

The limited analyses of this paper shed some light on this difficult aspect, and besides of (preliminary) “reasonable” comparative results, it is also concluded that other aspects must have been incorporated in the model, as evaporation rates, unsaturated flow through the surface soil layers, solar irradiance degrees, air humidity and so on. Indeed, not an easy problem to deal with. Nevertheless, as previously stated, encouraging results have been found, even with the usage of a “simple” geotechnical model that could take into consideration (at least) the soil's suction phenomena. There was a direct correspondence between displacements and suctions in the derived predictions, i.e., the displacements increased after rain events. The variation was not so abrupt, but it has demonstrated, particularly in the first top layers, where the saturation of the soil was more susceptible to changes, that displacements could indeed be influenced by such parameter.

Yet to be experimentally proved in the future, or by further (more complex) analyses, the percolation phenomena coupled to the evaporation of the soil (plus run off effects) tended to normalize the deposit's matrix suction after short period of rainy events, especially when such events were sporadic (non-continuous) and limited in time and reach (solely affecting the superficial layers). It can be concluded therefore that although simple, the constitutive hypoplastic model adopted herein suffice to simulate the behaviour of a typical pile curtain wall in the city of Brasilia, thus opening the possibility to allow local designers to forecast tendencies of performance at distinct temporal, seasonal and execution ranges.

The predictions also highlighted the importance to qualitatively study the results, given local variations in

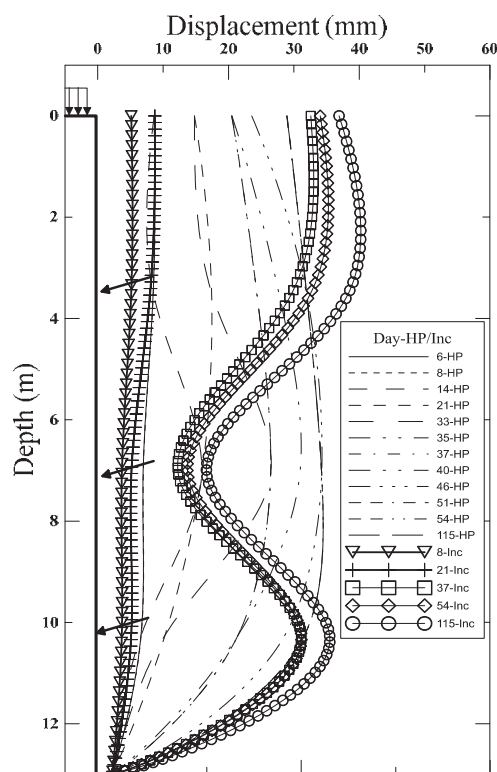


Figure 15. Displacements and numerical predictions in the curtain
Source: The authors

experimental x forecasted results that are of difficult matching (by localized effects or things that cannot be properly simulated in engineering terms). On overall terms, however, a reasonable match was found and the results did agree in qualitative terms, besides of small but perceptible quantitative differences (again denoting localized problems and/or limitations of the model). One point of curiosity was duly noticed herein: The numerical predictions tended to be less conservative than the experimental data results. This point however needs further confirmation.

The hypoplastic constitutive model, also proved to be a useful tool useful when it was necessary an approach to the modelling and simulation of a real case geotechnical structure built in a tropical laterized and unsaturated deposit. The input of the (close to real) rainfall patterns of this region in Brasilia during the wall's construction did indeed aggregate value to the analyses, increasing its accuracy power. Perhaps in the future, as stated before, other variables will also be taken on account.

Thus, depending on accuracy aspects or detailed (or not) behavioural tendencies that may be sought in such analyses, models with the soil/environment interaction will have to be adopted (somehow as done herein in a simplified manner). This aspect is of upmost importance when seasonality effects around the year need to be considered, or when the excavation takes place at a particular condition and a temporary curtain wall interacts with the surrounding environment at another distinct condition (dry x wet seasons, like the case of the present study). Perhaps other aspects will be required in future analyses, particularly when someone takes on consideration possible greenhouse influences that the climate might experience (or is already been experiencing).

Much can still be improved on top of the discussed preliminary results of the present paper, but one is already crystalized: the necessity of adopting more complex and rational models that do take on account the main aspects of behaviour of unsaturated tropical soils when loaded or unloaded, among them the soil's suction and the correct execution sequence of the problem.

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Development of domestic nutrition additives

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Abstract

This paper discusses the create a qualitatively new domestic lizotsim-contained natural biological corrector (NBC) with an effective use of its technology in the production of meat and dairy products competitive directional.

Keywords: natural biological corrector lizotsim-containing protein product; pectin-containing plant material; amino acid material; preventive effect.

Desarrollo de aditivos nutricionales domésticos

Resumen

Este trabajo analiza la creación de un nuevo corrector biológico natural interno, producto de la proteína que contiene lizotsim (NBC), con un uso efectivo de la tecnología en la producción de carne y productos lácteos direccionales.

Palabras clave: corrector biológico natural; producto de la proteína que contiene lizotsim; material vegetal que contiene pectina; material de ácido amino; efecto preventivo.

1. Introduction

One of the most actual problems of modern time is the preservation of human health that is largely determined by its nutritional status. Abnormalities in the structure of nutrition on the background of a complex biochemical and environmental conditions lead to the emergence and progression of a number of nutrition-related diseases [1-2].

The problem of contamination of the biosphere establishes a vital challenge-seeking means of health improvement of the population. This should be considered a fundamentally new approach to the construction of healthy food of the XXI century.

For regions with adverse environmental conditions is particularly relevant general preventive approach.

Global trends in nutrition associated with the creation of a product range of preventive, contributing to the improvement of health in daily use as part of their diet. The

high popularity of these products, according to the patent search, especially actual in developed countries such as USA, Japan and European Union countries. After all, foreign and domestic research found that increased erratic background radiation, entering the body of toxins, radioisotopes cause substantial alterations of protein, minerals, vitamins and other metabolic processes in the human body, but also lead to serious violations of the most important of his life hematopoietic system and digestive system [3-4].

In search of solution to the problem, scientists have come to the conclusion that the development of biotechnology, allowing to obtain from natural sources of biologically active substances are often deficient in the diet of adults and children, but necessary for the regulation of the functions of organs and systems of the human body.

Through the application of new, modern biotechnological approaches such products should contain small amounts of those nutrients or regulatory substances of animal and plant

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origin that are most deficient in a part of the daily diet of the organism, and may be a model of a balanced diet. It is necessary to take into account that the ingredient composition of the enriched complexes is best to use local raw materials, as it is at the genetic level mark in one degree or another body [5].

In the Republic of Kazakhstan the using of domestic production of a new generation of dietary supplements is virtually nonexistent. The market is full of imported products.

In this regard, the need for a scientific and technical basis for the production of domestic dietary supplement of natural origin is obvious [6-12].

Scientific and practical substantiation and resolution of these issues are considered in this scientific article.

The purpose of research is to create a qualitatively new domestic lizotsim-contained natural biological corrector (NBC) with an effective use of its technology in the production of meat and dairy products competitive directional.

There are the following tasks for the solution of this goal:

1. Investigate and justify the component composition of the NBC, which regulates preventive effect;
2. Determine the quality indicators and safety performance of the NBC.

2 Method

During the implementing the work there were used lizotsim-contained product obtained from chicken eggs and plant material (amaranth, pectin, rose hips, pumpkins, beta-carotene, kelp).

In the experiment there was involved the research of complex qualitative and safety indicators, used standard and original methods to get information about the composition and properties of the objects of research.

There were used the following methods:

Determination of lizotsim activity was carried out in terms of the activity of lizotsim using the reference strain micrococcus - *M. lysodeikticus* (strain 2665 SCI named after Tarasevich, Moscow).

Determination of minerals accelerated by using magnesium acetate.

The mass concentration of calcium and phosphorus were determined by atomic absorption spectrometry.

The amino acid composition was determined in hydrolysates of whole product with an automatic amino acid analyzer AAA-339.

For the determination of the bacteriostatic and bactericidal activity of the NBC there was used the photonephelometrical method. In our work, we take into account the change in the optical density of the culture medium with microorganisms and nutrient medium with the test NBC containing material and microbes immediately after connection and after 0-, 2-, 4- and 24-hour incubation. Pure cultures of *E. coli* and *S. aureus*, each individually plated on IPA and grown in an incubator at a temperature of 37°C for 24 hours. Then, it was rinsed with sterile isotonic sodium

chloride solution, and standardized to a content of 1 ml of 2 billion. microbial bodies. From this slurry was seeded on BCH tubes and grown hours in an oven at the above temperature.

There were used standard methods of microbiological parameters studies in accordance with GOST 9959-81; GOST 10.444-85; GOST 9958-81, GOST 9225-84, GOST 10444.11-89, GOST 10444.5-85 and GOST 30425, GOST RS0480-93.

Determination of sodium chloride was carried out in accordance with GOST 9957-73.

Vitamin content was determined by infrared spectroscopy instrument IK-4500 and method of high effective liquid chromatography on the chromatograph "MiLiChrome". According to the procedure that was developed by I.E. Mitin, N.A. Golubkina, there was determined the water soluble vitamins.

Determination of carbohydrates was performed by refractometerical method.

There was conducted research of indicators of ecological safety of the product to toxic elements:

- Mass fraction of mercury in accordance with GOST 26927;
- Mass fraction of iron in accordance with GOST 26928;
- Mass fraction of arsenic in accordance with GOST 26930;
- Mass fraction of copper in accordance with GOST 26931;
- Mass fraction of lead in accordance with GOST 269 322;
- Mass fraction of cadmium in accordance with GOST 26933;
- Mass fraction of zinc in accordance with GOST 26934.
- on hormones;
- Radionuclides for NRB-96.

The results obtained in this work were subjected to statistical processing. There were uses the absolute and relative values (extensive parameters). Evaluation of reliability of statistics carried out by means of arithmetic and geometric quantities (M), average error (m), ratio t according to Student, the level of probability of the confidence interval P. The association between the phenomena determined by the conformity ratio - criteria χ^2 .

3 Results

According to the actual issue of the NBC, we justified the choice of raw materials and component composition in its modeling, which consists of natural ingredients that are highly effective adaptogen, immunomodulator and biocorrector. The basis was the content therein in an optimum ratio of all necessary for the construction of essential protein molecule and nonessential amino acids, vitamins (B2, B6, C and D), and full-digestible mineral elements (calcium, phosphorous, magnesium, iron, etc).

During of the construction composite NBC used lizotsim-containing protein product, plant material (amaranth), pectin, rosehip, whey powder, a calcium product (kaltsid).

There was used lizotsim-containing protein product

derived from chicken eggs, which is the supplier of the protein simultaneously possesses unique antimicrobial properties, regulates the gut microflora. The action of lizotsim as a food preservative, due to the high antimicrobial activity to a wide range of microorganisms that pose a threat to human health, for example *Listeria* *togenes*, *Clostridium botulinum*, *Pseudomonas aeruginosa*, *Staphylococcus*, butyric acid bacteria, yeast and some other toxins.

Essential indicators on the quality of the finished product have all the ingredients of its prescription, but of particular importance and urgency of now acquires the quality of raw materials used in production. The quality of food is determined by a complex of characteristics, and above all, nutritional value, uniting biological and energy value, organoleptic and hygiene, microbiological and safety performance.

It was taken into account that the newly created products must meet the medical and biological requirements for food products functionality.

According to the concept of balanced nutrition for normal human life it is necessary not only to the intake of the necessary amounts of nutrients, but also the provision of certain relationships between them.

We modified the method of producing a protein product of hen egg lizotsim with high activity. To do this, in the technology of egg white after mixing and filtering operations included additional treatment, which obtained an innovative patent №22561 Committee on Intellectual Property Rights MJ RK.

Lizotsim retains its activity in said composition providing lysing action against Gram-positive and certain Gram-negative microorganisms. The introduction of the NBC Amaranth pectin plant raw material makes it possible to give the product dietary properties, as pectic substance capable of adsorbing various compounds.

There was conducted the analysis of plants (Table 1) with a purpose to obtain protein-vitamin complex (proteins, polysaccharides, flavonoids, amarantina etc.), from the amaranth leaves and then introducing it into the NBC.

By analyzing the relative performance of protein, amino acids, lipids, micro- macronutrients plants (amaranth, rice, corn, wheat and beans), as shown in Table 1 the energy value of 100 g in Amaranth is 439.0 kcal, which indicates a high complex score in relation to other plants.

Thus, the presence of plants (amaranth) allows you to enrich the composition of the NSC easily digestible protein, balanced in essential amino acids, vitamins, flavonoids, micro and macro. The presence of pectin helps recycling of heavy metals due to the presence of free carboxyl group (-COOH) is formed with metal ions few dissociating resistant compound chelates, which prevents the occurrence of heavy metals into the body. Amaranth flavonoid compounds have antioxidant activity, catalyzing the oxidation processes. The composition of the NBC includes whey proteins, which provide an additional source of essential amino acids and are recognized by immune carriers and antiseptic properties, which are able to glue the microorganisms and other foreign cells. Carbohydrate composition similar to that

Table 1.
Analysis of plants

Indicators	Vegetable raw materials				
	Amaranth	Rice	Corn	Wheat	Beans
Protein, %	15,5-23	7,60	7,68	13,00	21,48
Amino acids, mg/100 g.					
Tryptophan	1,50	1,20	0,70	1,20	0,00
Lizin	8,00	3,80	2,90	2,20	5,00
Gistidin	2,50	2,10	2,60	2,20	3,10
Arginin	10,0	6,90	4,20	3,80	6,20
Trionin	3,60	3,80	3,80	2,90	3,90
Valine	4,30	6,10	4,60	4,50	5,00
Methionine	4,20	2,20	1,40	1,60	1,20
Izoleitsin	3,70	4,10	4,00	3,90	4,50
Leitsin	5,70	8,20	12,5	7,70	8,10
Fenilalanin	7,70	5,00	4,70	5,30	5,40
Lipids, %	7,31	2,20	5,00	1,70	1,93
Ash, %	3,61	3,40	1,65	1,50	4,61
Calcium, %	0,14	0,02	0,01	0,02	0,15
Phosphorus, %	0,54	1,18	0,27	0,41	0,41
Magnium, %	0,22	0,08	0,13	0,10	0,19
Potassium, %	0,57	0,12	0,48	0,40	1,30
Natrium, %	0,12	0,01	0,01	0,01	0,20
Copper, ppm	6,00	4,00	4,00	4,20	10,0
Manganese, ppm	12,0	7,00	7,00	28,0	8,00
Zinc, ppm	21,0	24,0	24,0	41,0	32,0
Energy value, kcal / 100g	439,0	364,0	361,0	354,0	361,0

Source: The authors.

of whey milk. The principal carbohydrate is lactose - milk sugar a unique view, is not found anywhere in nature except in the milk. The whey from the milk pass vitamins, and water soluble to a greater extent than oil-soluble. Of the organic acids, it contains lactic, citric and volatile fatty - acetic, formic. Including the composite structure of the NSC kaltsid, we have provided the content of easily digestible compounds of calcium and phosphorus, which will significantly affect the metabolism, given that minerals are the basis of many of the structural and functional units of the body. Functions of minerals in the body are very diverse. They are involved in such dramatic reactions, like breathing, enzymatic and catholic decomposition and synthesis, muscle contraction, etc. With the ability to tightly bind to proteins, organic acids, calcium performs plastic role in the formation of tissue structures, maintaining their biocapacity, assimilation of nutrients, excretion of metabolic products and neuromuscular activity.

The implementing of pectin formulations rosehip in the NBC structure enriches it as a source of B vitamins and vitamin C. In addition, pectin depressing effect on the growth of enterobacteria opportunistic contributing to the restoration of normal intestinal microflora.

Thus, components that are used in modeling complex of NBC allow to obtain a product having a predetermined correcting properties (anemia, calcium or compatibility and gastrointestinal disease). Further it was needed to determine what quantities appropriate to include in the formulation ingredients to subject to the requirements of the chemical composition of the final product and the content of the individual ingredients to provide the minimum (maximum) optimization criteria based biocapacity.

Table 2.
Optimized formulations model NBC

The composition of the NBC	The ratio of components in the formulations of embodiments%		
	NBC -1	NBC -2	NBC -3
Lizotsim-containing protein product	50,0	38,0	25
Vegetable raw materials (amaranth)	8,0	10	15
Whey (dry)	40,0	50	58,0
Calcium-containing product (kaltsid)	1,5	1,5	1,5
Rosehip dry	0,5	0,5	0,5
Total	100,0	100,0	100,0

Source: The authors.

The formulating of the problem have been identified to solve the most important stages: selection criteria, study the list of ingredients, the collection of their characteristics and justification of restrictions on formulating.

Purpose of optimization of the formulations of the NBC is to get the product, balanced mineral composition, biological value recommended for children and adults with diseases caused by calcium deficiency, gastrointestinal diseases, anemia. As a result, the mathematical modeling of recipes found the optimal ratio between the ingredients in the formulations NBC-1, NBC-2, NBC-3 are shown in Table 2.

As a result of solving the problem have been several variants of model formulations NBC, which determine the expected values of the chemical composition and the value of the finished product.

There was studied the amino acid composition of the NBC, the results of which are shown in Table 3.

Analyzing the data of the table it can be concluded that the NBC proteins contain a complete set of essential amino acids, which is quick for limiting amino acids is at least 82%.

There are three types of formulations NBC also studied the chemical composition (mineral and vitamin).

Analysis of the chemical composition of the NBC of the table shows that the mineral composition of 100 g NBC provides the need for minerals by 30% of the daily rate of 100%.

Because the mineral composition of the NBC-1 provides nearly 100% of the body's need for phosphorus, 60% - calcium, magnesium. High levels of these minerals will allow to fill the shortage of calcium and phosphorus when entering it in the diet.

Most calcium, iron and magnesium contained in NBC-2. The presence of high magnesium content creates the most favorable conditions for the absorption of iron. NBC-2 contains the most balanced composition of calcium to phosphorus ratio of 1: 1, which best promotes the absorption of calcium.

Vitamin composition of all three variants of the NBC for certain types of essential vitamins, 50-60% provides the body's need.

Based on an analysis of data on the ratio of essential amino acids, minerals and vitamins from the three options presented by the NBC, preference is given to an embodiment of the NBC-2, the results of which are shown in Table 4.

Table 3.
The amino acid composition of the NBC

Essential amino acids	Quantity of amino acids, mg for 100g of product		
	Recipes of NBC		
	NBC -1	NBC -2	NBC -3
Valine	22,9±0,12	17,3±0,08	11,9±0,08
Izoleitsin	25,3±0,12	15,3±0,05	13,5±0,08
Leitsin	44,5±0,21	22,3±0,08	24,8±0,09
Lizin	33,1±0,15	16,0±0,07	17,9±0,08
Methionine	12,4±0,08	10,1±0,04	4,2±0,03
Threonine	83,0±0,23	11,7±0,05	41,9±0,14
Tryptophan	61,4±0,18	58,5±0,03	31,7±0,08
Phenylalanine	16,2±0,11	15,9±0,09	7,3±0,08
Nonessential amino acids, limited			
Cistine	9,2±0,06	6,2±0,05	4,4±0,04
Thirosine	13,2±0,08	6,8±0,05	7,8±0,05
Scor of limited amino acids			
Metionin+Cistine	13,4±0,08	13,8±0,08	11,9±0,08
Valine	9,9±0,07	10,3±0,07	11,0±0,04

Source: The authors.

Based on the formulations developed models held production of pilot batches of the c under experimental conditions.

NBC produced according to our biotech production, which is as follows: the reception and evaluation of the quality of raw materials, which comprises mixing the components in the specified ratio, technological processing of raw materials and packaging.

Production of the NBC at the existing processing plants do not require any special technological equipment.

As raw materials used: eggs, vegetable raw materials (amaranth), whey powder, a calcium product (kaltsid), hips (krio powder).

In the process of developing lizotsim-containing materials carefully conducted acceptance and sanitize surfaces of eggs. Then the eggs are separated into yolk and white. The separated protein was subjected to a sensory evaluation, filtering and mixing. The protein was then coagulated by adding thereto lactic or citric acid to pH 4-5 and sodium chloride in an amount of 0.2-0.5% by weight of protein. The resulting mass was heat-treated in an oven at a temperature of 55-60°C for 35-40 minutes.

As a result of the drying of the protein mass becomes soft fine-grained, white with a touch of lemon, with a sour taste and smell characteristic of the product.

Develop powdery mass was cooled to ambient room temperature (20-25°C).

Amaranth leaves sort, culled damaged, rotten, then dried in a drying equipment with forced ventilation at a temperature of 25-30°C or in air. The dried leaves were ground to a powder. Since kaltsid, krio powder and rose hips are ready-to-use forms, the preparatory process steps are not required.

All of the components included in the NSC was thoroughly mixed for 2-3 minutes, packed and packaged. No contraindications.

Thus, on the basis of theoretical and experimental researches the science-based formulations and biotechnology production of new food additives - natural biological corrector (NBC) for the prophylaxis of iron, calcium deficiency and diseases of the gastrointestinal tract.

Table 4.

Chemical composition of natural biological corrector

Chemical composition of NBC-2	Units of measurable	Lizotsim-containing protein product		Milk serum		Amaranth	
		Quantity in 100 gr.	Quantity of NBC	Quantity in 100 gr.	Quantity of NBC	Quantity in 100 gr.	Quantity of NBC
Proteins	%	82,4	31,3	7,8	3,9	15,0	1,5
Fats		-	-	1,1	0,6	4,1	0,4
Carbohydrates		-	-	73,3	36,7	2,1	0,2
Calcium	Mg	74,8	28,4	1100,0	550,0	140,0	14,0
Phosphorus		1340,0	509,0	1200,0	600,0	540,0	54,0
Potassium		1067,0	405,5	1400,0	700,0	570,0	57,0
Sodium		1297,0	492,9	1100,0	550	120,0	12,0
Magnesium		71,0	27,0	150,0	75,0	220,0	22,0
Ferrum		1,1	0,4	1,5	0,8	-	-
Vitamin B ₂	Mg	-	-	1,8	0,9	0,24	0,02
Vitamin C	Mg	-	-	5,0	2,5	21,6	2,2
Vitamin D	Mg	-	-	-	-	-	-
Vitamin B ₆	Mg	-	-	-	-	-	-
Energy value	Kcal	102,0	38,7	346,0	173,0	439,0	43,9

Source: The authors.

Continue Table 4.

Chemical composition of NBC-2	Units of measurable	Calcium-containing product		Rosehip dry (Krio powder)		Quantity of NBC in 100 gr.	Quantity in 100 gr. of product
		Quantity in 100 gr.	Quantity of NBC	Quantity in 100 gr.	Quantity of NBC		
Proteins	%	2,1	0,03	4,0	0,02	36,75	2,9
Fats		-	-	-	-	-	-
Carbohydrates		-	-	60,0	0,3	37,6	3,0
Calcium	Mg	37300,0	559,5	66,0	0,3	1152,2	92,2
Phosphorus		166,0	2,5	20,0	0,1	1165,8	93,3
Potassium		93,1	1,4	58,0	0,3	1164,2	93,1
Sodium		130,8	1,0	13,0	0,1	1056,9	84,5
Magnesium		412,9	4,1	20,0	0,1	128,2	10,3
Ferrum		-	-	28,5	0,1	1,3	0,10
Vitamin B ₂	Mg	1,2	0,01	2,84	0,01	0,94	0,07
Vitamin C	Mg	30,0	0,5	1200,0	6,0	11,2	0,89
Vitamin D	Mg	50,0	0,8	-	-	0,8	0,06
Vitamin B ₆	Mg	1,3	0,01	-	-	1,6	0,12
Energy value	Kcal	85,2	1,3	253,0	1,3	258,2	20,7

Source: The authors.

The analysis has been chosen are the ingredients that make up the formulation, in accordance with modern concepts of nutrition with the simulation recipes NSC.

The biotechnology a composite NBC achieves its high level of quality (Table 5).

Reduced consistent with lower acid numbers developed by the NBC and determines, among other factors, its greater stability to oxidative damage and other negative processes occurring during storage.

It was found that the prototypes of NBC after generation and storage throughout the month 1,3,6 comply with San PIN number 2: 3.1078 - 01 in terms of the number of mesophilic aerobic and facultative anaerobic organisms (not more than 5×10^4 COE/g).

The change in product quality and sanitary and hygienic safety during storage has important microbiological stability. In this regard, studies were conducted to determine the amount mesophilic aerobic and facultative anaerobic microorganisms (QMAFAnM) and the presence of coliform (CGB), childbirth Salmonella, Clostridium и Staphylococcus.

Table 5.

The safety and quality of NBC

Indicators	Received	Regulated by SanPin 2.3.2.1078-01
<i>Organoleptic characteristics</i>		
Appearance, texture	The bulk homogeneous powder. Allowed the presence of small lumps, easy break under mechanical stress	
Color, taste, smell	Color milky white uniform throughout the mass of the powder. Taste sweet, odorless.	
<i>Physical and chemical parameters</i>		
Moisture content, %	3,50±0,05	No more than 5
Solubility, sec	48±5	No more than 60
The acidity of the recovered product pH	6,6 – 6,8	–
<i>Microbiological parameters</i>		
KMAFAnM, CFU/r	1,5×10 ²	No more than 5×10 ⁴
Content of yeasts and molds in 1.0 g of BAP, CFU	Not found	No more than 20
Coliform bacteria in 1.0 g	Not found	Not allowed
S. aureus in 0,1 r BAP	Not found	Not allowed
Pathogenic microorganisms, including Salmonella in 25.0 g of BAP	Not found	Not allowed

Source: The authors.

Table 6.
The sanitary-chemical and radiological safety parameters of NBC

Indicators	Content in HBC, mg/kg	MPC on toxic elements, mg/kg
Toxic elements:		
Lead	0,02	0,10
Cadmium	0,01	0,05
Quicksilver	Not found	0,05
Copper	Not found	1,00
Arsenic	Not found	0,10
Zinc	Not found	10,0
Pesticides:		
HCH (sum of isomers)	0,005	0,200
Heptachlor	Not found	Not allowed
DDT and metabolites	Not found	0,2
Micotoxins:		
Aflatoxin Bi	Not found	0,0050
Zearolenon	Not found	1,00
<i>Radiological parameters</i>		
Parameter	Content in HBC, Bk/kg	Allowed level, Bk/kg
Caesium – 137 / Strontium-90	3,6±0,04	200,0
	1,0±0,01	100,0

Source: The authors.

The results of microbiological studies suggest that the use of the ingredients of the component composition of the NBC does not lead to a decrease in sanitary conditions, and the number of microorganisms complies with the microbiological criteria for assessing the purity of NBC during the storage period.

The evaluation results of the NBC sanitary and chemical safety are given in Table 6.

It should be noted that the sanitary-chemical and radiological characteristics of the NSC are normal.

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- Un Algoritmo GRASP híbrido para el 2eCVRP
- Procedimiento para la priorización de Factores Críticos de Éxito
- Estudio comparativo de las propiedades mecánicas de la resina poliéster reforzada con fibra de bambú, como material sustituto de la fibra de vidrio.
- Optimización de mezclas para la producción de pavimentos a través de modelos de programación lineal
- Asociación entre las incomodidades corporales y los factores de riesgo laboral en trabajadores de mataderos de aves
- Modelado de tráfico del servicio de video bajo demanda mediante NS-3
- Remoción de hidrocarburos de aguas de producción de la industria petrolera utilizando nanointermedios compuestos por SiO₂ funcionalizados con nanopartículas magnéticas
- Clasificador de llamadas VoIP para calificar un proveedor basado en Support Vector Machine
- Diseño y optimización de una pila de electrodialisis inversa para generación de energía a partir de gradiente salino
- La condensación y el cambio en la presión parcial como causa principal del flujo de aire: Evidencia experimental
- Modelos de optimización para sistemas de potencia en la evolución hacia redes inteligentes: Una revisión
- Secado convectivo de zapallo (*Cucurbita moschata*): Influencia de la temperatura y velocidad de aire sobre la difusividad efectiva de humedad, contenido de carotenoides y fenoles totales
- Consumo de energía y calidad de servicio en redes WBAN: Una evaluación de desempeño entre capa cruzada e IEEE802.15.4
- Simulación hidrológica e hidráulica para el diseño de macrodrenaje para la gestión y recuperación de cárcavas
- Evaluando aproximaciones basadas en aprendizaje supervisado para la fusión en el dominio espacial de imágenes multi-foco
- Contenido foliar de N, P y K en algodón fertirrigado con efluente de alcantarillado tratado
- Caracterización microestructural, mecánica y de desgaste de recubrimientos de CuxAly depositados mediante proyección térmica
- Cooperation strategies featuring optimization in the school transportation system in Bogota
- Diferencias entre compradores y no compradores en el comercio electrónico en Colombia: El efecto moderador del nivel educativo y del estado socio-económico en la intención de compra electrónica
- Implantación de elementos de sostenibilidad aplicados a la modernización de áreas productivas: España, un caso deficitario en la Europa del sur
- Un modelo de toma de decisión multiperíodo basado en 2-tupla lingüística para la selección dinámica de proveedores verdes
- Primer acercamiento a la mecánica de contacto en amputados transfemorales unilaterales
- Evaluación de la eficiencia de ciencia, tecnología e innovación mediante Data Envelopment Analysis (DEA): Caso Colombia
- Evolución del modelo de zonas francas permanentes en el mundo: Con un énfasis en el caso Latinoamericano
- Control combinado de un sistema de almacenamiento de energía flywheel y una batería de flujo redox de vanadio para aplicaciones de energía eólica en microredes
- Estudio comparativo del desgaste en mezclas erosivas de recubrimientos depositados por HVOF
- Aplicación de la gestión de riesgo a equipos y sistemas productivos
- Estudio numérico y experimental del ensayo de compresión del cobre, método de contacto mortar
- Inmovilización de elementos de reconocimiento en una bio-plataforma basada en capas auto-ensambladas
- Metadatos estadísticos en el descubrimiento de conocimiento
- Predicción clase A de una estructura de contención en pilotes ejecutada en suelo tropical