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Resilient Module Soil-Cement Prediction based on Setting Temperature

Predicción del Módulo Resiliente del Suelo Cemento en función de la Temperatura de Fraguado

Liliana Carolina Hernández García[1] and Nelson Fernando Lizarazo Salamanca[2]

ABSTRACT

This research correlates the setting temperature of the Soil Cement (SC) with its resilient modulus, based on the maturity index of three mixtures made with different types of cements: general use, High Early Resistance, and Moderate Heat of Hydration. Each mix design has a compressive strength of 4,5 MPa at 7 days of age and durability measured with the 10% wetting and drying test. The method consisted of curing the samples of the three mix designs at three different temperatures -11, 30, and 40 °C- and then monitoring the development of the temperature within the samples during the first thirty hours. At 28 days of age, the resistance modulus of the samples was measured with cyclic triaxial equipment. After analyzing the results, a linear equation was deduced which would facilitate quality control during the construction process. This prevents microcracking of the compacted layers, since their fracturing is not necessary during the extraction of nuclei and field density tests.

Keywords: soil cement, setting temperature, resilient module, heat of hydration, resilience

RESUMEN

Esta investigación correlaciona la temperatura de fraguado del Suelo Cemento (SC) con su módulo resiliente, a partír del índice de madurez de tres mezclas fabricadas con diferentes tipos de cementos: uso general, Altas Resistencias Tempranas y Moderado calor de Hidratación. Cada diseño de mezcla cuenta con una resistencia a la compresión de 4,5 MPa a los 7 días de edad y una durabilidad medida con la prueba de humedecimiento y secado del 10 %. El método consistió en curar las muestras de los tres diseños de mezcla en tres temperaturas diferentes -11, 30 y 40 °C- para luego monitorear el desarrollo de la temperatura al interior de las muestras durante las primeras treinta horas. A los 28 días de edad, se midió el módulo resiliente de las muestras con equipo triaxial cíclico. Tras analizar los resultados, se dedujo una ecuación lineal que facilitaría un control de calidad durante el proceso constructivo. Esto evita la micro fisuración de las capas compactadas, ya que no es necesario fracturarlas durante la extracción de núcleos y las pruebas de densidad en campo.

Palabras clave: suelo cemento, temperatura de fraguado, módulo resiliente, calor de hidratación, resiliencia

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Introduction

The ASTM D6236-11 (ASTM International, 2011) guide states that control of the final resistance of Soil Cement (SC) must be carried out by extracting nuclei in the field after its maturation stage, and that its results must be compared with a mixture design validated in a laboratory (Emmert et al. 2017). However, the resistance of Soil Cement (SC) is influenced by multiple factors, such as the type of cement and its quantity in the mix, the water content, the degree of compaction, the uniformity of the compacted layer, the curing conditions, and the age of maturity (Ghanizadeh, Rahrovan, and Bafghi, 2018; Linares-Unamunzaga, Pérez-Acebo, Rojo, and Gonzalo-Orden, 2019; Estarbragh and Ranjbari, 2017). That is why waiting for the mixture to reach 28 days of age is a method that delays the construction process of any infrastructure project.

In order to speed up the construction procedure, the ACI 230 Committee (2009), recommends carrying out a density control on site as soon as the compaction process is completed, either by the ASTM D2922 nuclear method (ASTM International, 2005), the ASTM D1556 sand cone method (ASTM International, 2015a) or the ASTM D2167 rubber ball method (ASTM International, 2015b). However, for any of the above, the test requires fracturing of the compacted layer to open a hole in the surface, causing the bonds that form between the cement and the ground to break during the first adjustment. This results in early microcracking.

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This pathology is accompanied by the plastic behavior of the soil type, since it causes contraction and subsequent cracking during the drying process, thus increasing the surface roughness. To prolong the life cycle, it is necessary to maintain a relationship between the smoothness of the pavement and its resistance. As a road gets rougher there is a greater resistance to rolling between the pavement and the vehicle, thus affecting its durability (Akbarian et al., 2019). A bituminous layer is applied to reduce friction, but the cracks leave a scar on the surface, which reduces its useful life.

In order to avoid the extraction of nuclei and the fracturing of the layer during the control of field densities, an analysis of the SC layer as a material whose resistance is acquired through an exothermic reaction is proposed. Although hydraulic cement is known to be composed of calcium silicate phases, Alita and Belita, the former reacts relatively quickly with water and is responsible for the first resistances after a process of heat release due to multiple simultaneous chemical reactions. The second is less reactive at early ages but contributes to strength later on. In order to meet the requirements of current infrastructure works, industrialized cements have an increasingly high content of Alita, and the temperature of the mixture is increased during the adjustment process to achieve high early resistances. (Concrete Sustainability Hub, 2014; Teixeira, Santilli, and Puente, 2016).

On the other hand, it is known that, in addition to the evolution of heat due to the exothermic reaction of cement, ambient temperature has a direct impact on the evolution of mechanical resistance. Experimental tests have revealed that concrete achieves a higher resistance when exposed to high temperatures (40 °C), whereas the opposite occurs when it cures at low temperatures (5 °C). This is how Yikici and Chen (2015) recorded controlled temperature monitoring in massive concrete, where they identified that, in the places near the surface, the temperature of the mix was closer to the ambient temperature, and therefore the resistance of the nuclei extracted from the center registered higher resistances than those taken near the surface (Boubekeur, Ezziane, and Kadri, 2014).

Furthermore, the production of hydraulic cement appropriates the development of additions, also known as Supplemental Cementitious Materials (SCM), such as Nanosilica (NS), fly ash, silica fumes, among others, to improve efficiency and reduce Clinker consumption. Furthermore, since the content of nanoparticles in hydraulic cement improves the development of compression strengths, this reduces the number, degree of crystallinity, and size of portlandite crystals, causing a high pozzolane activity that accelerates the formation of Tobermorite (CHS) and the process of hydration, which results in a reduction of the heat of hydration in the mixture (Juenger et al., 2012; Sánchez Cotte, Torres Chueco, and Esquivel Ramírez, 2019; Abdolhosseini Qomi, Bauchy, and Pellenq, 2018).

Consequently, in order to guarantee environmental sustainability as a goal for 2030, hydraulic cement producers are studying the incorporation of pozzollanic materials from industrial waste to reduce emissions of CO_2 (United Nations, 2015). These include masonry waste and other ceramics, since they indicated a clear variation in the thermal properties of the mixture, improving its resistance and increasing the density of the final product. (Pérez Carrión, Baeza Brotons, Garcés Terradillos, Galao Malo, and Payá Bernabeu, 2013). All this in order to promote the recycling of materials during the construction and rehabilitation of pavements. (Zhang, Han, Yu, and Wei, 2018; Silva, Izquierdo, and Delvasto, 2019; Pérez Carrión et al., 2013; Jones, Louw, and Wu, 2015; Tobón, Restrepo Baena, and Payá Bernabeu, 2007).

To summarize, a wide variety of added cements are available which, depending on their mechanical performance, register a greater or lesser release of heat during their adjustment, tracing a different temperature curve. But, while it is true that the resistant capacity of the Soil Cement layer should be measured as the amount of deformation that is recoverable or resistant to a dynamic cyclic load of vehicular traffic, and not as a point compression load, it is proposed that its resistance is correlated with a resilient module (Mr), since it is an important factor when designing thicknesses according to the empirical-mechanical pavement design guide. This becomes a measure of how the proposed pavement should react and of the tracing underlying rapidly applied loads, such as the ones related to traffic. (AASHTO, 2020) and (Reeder, Harrington, Ayers, and Adaska, 2019).

That is why it is estimated that the resilience of a SC mix is determined by the cement content and the density after compaction measured with field tests, where a low density implies a lower Mr. Therefore, the resistance modulus is a function of the development of strengths after an exothermic reaction, which is related to the Alite content, the content and type of the supplemental cement material or addition, and the ambient temperature where the layer was installed.

To evaluate this hypothesis, three commercially available hydraulic cements were chosen: general-purpose cement (UG), high early resistances (ART) and moderate heat of hydration (MCH). These are standardized by NTC 121 (Icontec International, 2014), as a modified adoption of ASTM C1157 (ASTM International, 2020). Each one presents a different development of maturity, resistance and heat of hydration, since they are materials valued for their mechanical performance and not for their chemical product.

Experimental Program

Mixture proportioning

The procedure began with the design of the mixture with each type of cement whose compressive strength is adjusted to 4,5 MPa at 7 days of age. The employed soil was a selected material (A-25), classified as coarse sand with low compressibility clay, which, for this work, constituted a constant in the investigation and abode by the ACI 230 procedure. The following dose was established for each of type of cement:

Table 1. Dosing of the SC for the preparation of samples for the resilient module

Cement type	Maximum density (gr/cm^3)	Soil (A-25)	Cement	Water
MCH	1,861	2 000 gr	800 gr	200,0 gr
UG	1,907	2 000 gr	700 gr	150,0 gr
ART	2,057	2 000 gr	600 gr	240,0 gr

Source: Authors

Soil Cement maturity

The term 'maturity' is understood as the relationship between the evolution of concrete strength as a function of age with the development of temperature (Sota, Avid, Moreira, and Chury, 2016). The method for defining concrete maturity is standardized by ASTM C1074-19 (ASTM International, 2019), and it is used to project and estimate hydraulic concrete strengths by recording the history of temperatures taken on site from the time the mixture is prepared to its final ripening (Lee and Hover, 2016).

In total, 54 cylinders were made for each mix design. 18 were cured in a humid room with a controlled temperature of 11 °C, 18 in a humid room at 30 °C, and the remaining 18 at 40 °C. These samples failed single compression at 1, 3, 4, 8, 16 and 32 days of age, in a series of three cylinders for each age, as described in procedure ASTM C1074-19. According to current test standards, there are two ways of determining the maturity of concrete strength, which measure how temperature affects the hydration rate. The first one assumes that the rate of hydration is a linear function of temperature, while the second, that it obeys the Arrhenius exponential equation (Icontec International, 2002).

The resistance prediction model, which assumes a linear function, is based on the temperature factor and applies the maturity index equation (Equation 1):

$$M(t) = \sum (T_a - T_0)\Delta t \quad (1)$$

where M is the maturity index that can be measured in days or hours; T_a is the average of the monitored temperature of the concrete in a time interval Δt; T_0, the calculated reference temperature; and Δt is the time interval in which the temperature recording was performed.

The Arrhenius exponential equation, in turn, determines the equivalent age with the following Equation 2:

$$t_e = \sum e^{-Q\left(\frac{1}{T_a}-\frac{1}{T_s}\right)}\Delta t \quad (2)$$

where t_e is the age equivalent to the specified temperature T_s in hours, Q is the activation energy divided by the gas constant in degrees Kelvin, and T_a is the average temperature of the concrete in degrees Kelvin over a time interval Δt of one hour, T_s is the temperature specified in the prediction in degrees Kelvin, and Δt is the time interval in hours.

With the results obtained from the compression test of cubes, after making the graphs of the inverse of the resistance as a function of the inverse of the temperature and the calculation of the Limit Resistance (Su) and the constant K, we proceeded to estimate the value of the constant Q from the linear curve of the logarithm of K as a function of the inverse of the temperature in degrees Kelvin.

The slope of each of the lines in Figure 1 corresponds to the activation energy value divided by the gas constant Q, so that, for the SC made with ART cement, it amounted to 3 056,2 K, 2 227 K for the SC with UG cement, and 1 711,6 K for the SC with MCH cement. These values were multiplied by the constant of Arrhenius ideal gases (8,31J/(K.mol)). The obtained activation energy of the SC-ART was 25 397; for the SC-UG, 18 511; and for the SC- MCH, 14 223 (Hernández and Lizarazo Salamanca, 2019). For a Portland cement, this value is usually between 40 000 and 45 000 J/mol (ASTM International, 2019). Therefore, the activation energy of the samples was significantly reduced due to the influence of the soil and the low water content in the reaction.

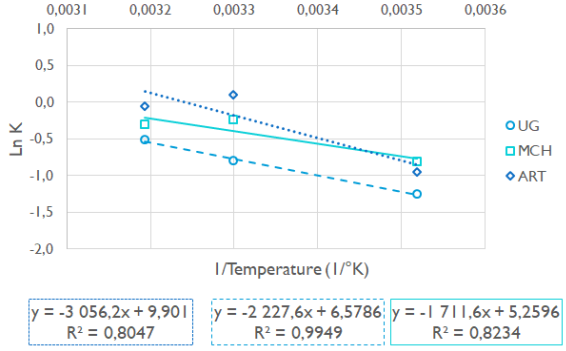

Figure 1. K values vs. cure temperature to determine the constant Qused in the calculation of the temperature-time factor for the three types of SC.
Source: Authors

Temperature monitoring

Temperature monitoring was carried out during the first 30 hours of mixing. The samples, compacted in paper containers, were measured so that the external temperature was transferred to their interior. The container was 10 cm in diameter and 5 cm in height, and the material was compacted into three layers, each 2 cm tall, using a metal rammer with a mass of 340 g with a flat circular surface and a 25 mm diameter (Hernández and Lizarazo Salamanca, 2019). Then, the samples were placed in three humid rooms: the first, at a temperature of 40 °C, using the water bath equipment (Figure 2); the second, in an airtight container at 11 °C in a refrigerator; and the third in a humid room at a temperature of 30 °C. Finally, the temperature sensors were installed and, with help from a Data logger indicator, the records were made during the first thirty hours of age.

The setting was defined according to norms such as the time need, from the beginning of the mechanical kneading, for the penetration of a cylindrical steel needle into cement paste of normal consistency to reach the specified values, both at the start and the end of the setting. This tends to happen in

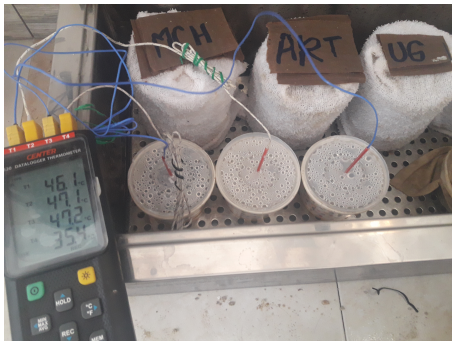

Figure 2. Temperature record.
Source: Authors

conventional concrete from 50 minutes up to 8 hours (SanJuan Barbudo and Chincon Yepes, 2014). However, SC is a hybrid for which, given the activation energy, thixotropy, cohesion, and compaction, the variation of the initial and final setting temperature extends to the first 30 hours, as it approaches ambient temperature. With the records of the temperatures monitored until the first 30 hours, we proceeded to calculate the age factors and equivalent age factor of equations (1) and (2).

It is necessary to clarify that the specified temperature T_s corresponds to 22 °C, since it was the temperature at which the samples failed the resilient module test, to which the correlation is to be made.

Resilience Module

However, the maturity of the resistance measured with this method corresponds to the uniaxial load applied during compression. To predict resilience, it was necessary to subject the three mixture designs to the same curing conditions. To this effect, temperature measurements were set for 28 days of age, and then the mixtures were subjected to cyclic loads using the resilient modulus test according the AASTHO T307-99 method (AASHTO, 1999). The results registered a variation in the slope between the ratio of the stress invariant equivalent to the amplitude of the load and the resilient modulus obtained after 100 load applications per cycle. This variation differs between the types of cements and the curing temperatures, as shown in Figure 3.

The way to determine an exact figure for the final resilient modulus was choosing the invariant of the stress, given that the deflection stress is produced by the pavement structure and the overload generated by the passage of the vehicle wheel (Guzmán Suárez and Higuera Sandoval, 2016) and, for mixing design purposes, the load corresponds to 4,5 MPa. Thus, with each of the linear trend equations, the corresponding Mr at $\theta = 450$ kPa was calculated for each sample.

The result was tabulated with the most relevant data from the maturity test and with the temperatures recorded during the first thirty hours (Table 2).

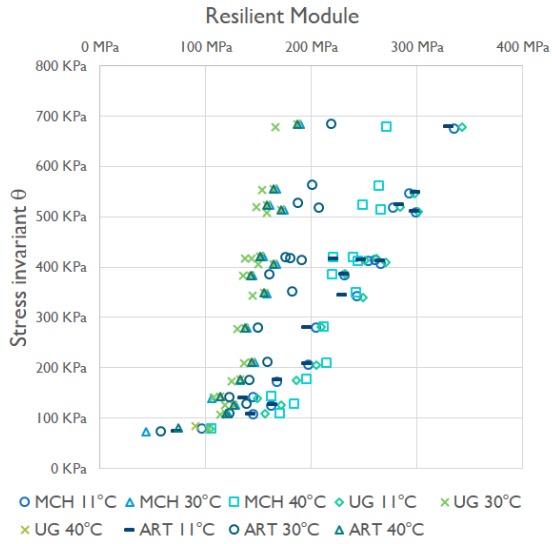

Figure 3. Relationship between the resilient modulus of the SC cured at different temperatures and the invariant stress.
Source: Authors

Prediction Model

To establish a correlation factor, the difference between the maximum and minimum internal temperature was calculated, which, for this work, will be called Temperature Increase (ΔT). And with these results, the maturity factor and the maximum and minimum age factor were recorded for each of the corresponding specimens. Likewise, the following equations were deduced:

$$\Delta T = T_{\max(30\ hours)} - T_{\min(30\ hours)} \quad (3)$$

where ΔT is the increase in temperature recorded during the first 30 hours of age, $T_{\max}$. It is the maximum temperature recorded in °C within the same time interval. $T_{\min}$ is the minimum temperature recorded in the same period of time.

Table 2. List of results obtained with the Soil Cement samples cured at different temperatures

Cement Soil	$T°$ Ambient	Mr (450 kPa)	ΔT_{max} (30 hours)	Maximum maturity factor	Maximum age factor	Maturity factor x ΔT_{max}	Age factor x ΔT_{max}
MCH	40	232,93	8,1	1,6569	41,10	13,42	332,9
MCH	30	235,64	10,1	1,2294	32,48	12,41	328,0
MCH	11	255,13	12,7	1,4250	36,63	18,09	465,2
UG	40	162,00	1,6	1,6098	31,91	2,57	51,1
UG	30	165,82	5,3	1,2137	23,81	6,43	126,2
UG	11	272,14	15,3	1,4250	28,31	21,80	433,2
ART	40	173,62	3,1	1,6528	30,19	5,12	93,6
ART	30	193,06	6,3	1,2362	32,48	7,78	204,6
ART	11	280,43	11,4	1,4250	36,63	16,24	417,5

Source: Authors

After organizing and running relative difference calculation models, it was determined that, due to the increase in temperature ΔT, the most favorable curve is the product

between the maximum maturity factor obtained from the temperature measurements during the first 30 hours, for which the Resilient Module (Mr-450) is graphed as a function of the product. It was called 'setting maturity factor' for this investigation, as shown in the Figure 4. In this way, a second equation is in order, which is defined as the following expression:

$$FM_F = \Delta T \cdot FT_{\max} \quad (4)$$

where FM_F is the setting maturity factor, ΔT is the temperature increase in °C recorded during the first 30 hours of age and calculated from Equation (3), and $FT_{\max}$ is the maximum temperature factor calculated every 0,5 hr for the same time interval using Equation (1).

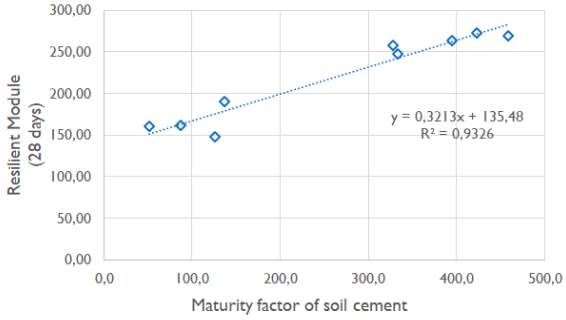

Figure 4. Relationship between the Maturity Factor and the resilient module at 28 days.
Source: Authors

In the same way, the product is related with the maximum equivalent age factor obtained during the first 30 hours and the temperature increase ΔT, which for this research is called 'setting age factor' as a function of the resilient module. To this effect, the following equation is deduced:

$$FE_F = \Delta T \cdot FE_{\max} \quad (5)$$

where FE_F is the setting maturity factor, ΔT is the temperature increase in °C, and $FE_{\max}$ is the maximum age factor calculated in 0,5-hour intervals according to the Arrhenius equation over a period of 30 hours. With the two trends, the prediction equations of the Resilient Modulus of the SC are established as a function of the maximum setting maturity factor and as a function of the maximum setting age factor, with the following equations:

$$Mr(450\ \text{kPa}) = 0{,}3213\ FM_F + 135{,}48 \quad (6)$$

where Mr is the resilient modulus with a stress invariant of 450 kPa at 28 days of age and Fm is the calculated maturity factor of Equation (4) during the first 30 hours.

$$Mr(450\ \text{kPa}) = 5{,}2661\ FE_F + 147{,}73 \quad (7)$$

where Mr is the resilient modulus with a stress invariant of 450 kPa at 28 days, and FE_F is the setting age factor, calculated from Equation (5). To verify the prediction model, the line was drawn between the resilient modules calculated from Equations (6) and (7) as a function of the resilient modules measured in the laboratory, as shown in Figure 6 indicating 89,3% as the reliability of the method.

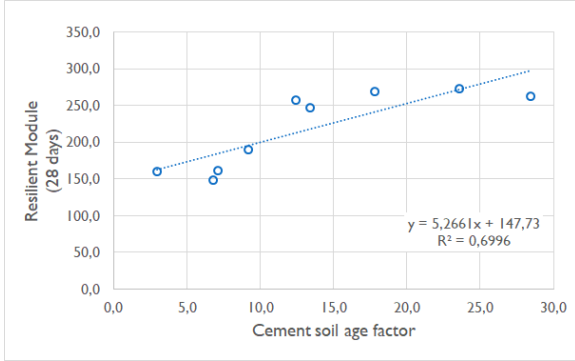

Figure 5. Relationship between the Age Factor of setting and the Resilient Module at 28 days.
Source: Authors

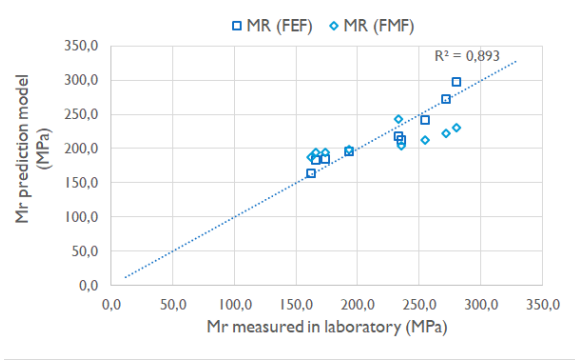

Figure 6. Comparative between calculated and measured Mr in laboratory.
Source: Authors

Conclusions

Looking at linear Equation (6), a close proportionality can be found between the increase in temperature during setting with the maturity index and the resilient modulus recorded at 28 days of age.

Comparing the two methods to calculate maturity proposed by ASTM 1079, the one with the highest reliability for predicting the resilient module is the one that uses the maturity factor with 93,26%, while the model that only uses the age factor registers 69,96%.

According to the consolidated results in Table 2, the cement with the lowest Clinker content and added with lime (MCH), registered a similar temperature increase in the three environmental curing conditions, as well as the fact that, in the resilience tests, it was the only mixture that did not register major changes in its results, despite being cured at three different temperatures. This suggests that the ambient temperature does not affect the resilience of the SC-MCH mix, while with the two cements that have the highest Clinker content, the ambient temperature was a variable that directly affected its performance.

The greater the temperature increase recorded during the setting phase of the SC, the greater the resilient modulus at 28 days of age, thus making it a directly proportional variable. In other words, thinking about increasing the temperature

in the SC mixture during its construction stage mechanically could bring better results in its performance, as long as it does not reach the point of thermal contraction in the case of cohesive soils. For this reason, it would be recommended to hydrate the material with steam or, if that fails and the tools are not available, to heat the curing water that will spread over the mixture for compaction.

With this method, the possibility of performing a quality control on site through non-destructive tests is available, maintaining the development of multiple reactions and monitoring the evolution of heat through the recording of temperatures that involve the type of cement at room temperature. Consequently, with mobile devices and temperature sensors, its final resistance can be predicted as a pavement structure during the installation of the SC layer. However, this must be validated with different types of soil.

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Refining of the solid fraction of sheep feces digestates from an anaerobic digester

Refinación de la fracción sólida de digestatos de excretas de ovejas proveniente de un digestor anaerobio

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ABSTRACT

Anaerobic digestion is a technology used in the degradation of organic waste, with the possibility of obtaining products such as biogas and digestates, which have significant nutrient concentrations. However, using them without any prior treatment can cause various problems, due to the presence of unstabilized organic matter and excessive concentrations of nutrients reaching phytotoxic levels, as well as water and air contamination. Therefore, in this work, we present a refining process of solid digestates from a biodigester fed with sheep feces, by means of vermicomposting, in combination with plant waste, and using earthworms of the species *E. andrei* and *E. fetida*. The digestate values at the end of the vermicomposting showed to be within optimal ranges of electrical conductivity, with values ≤4 dS/m. The pH values were between 5,39 and 7. The percentage of organic matter was between 20 and 50%. It could be proven that the refining process increased the concentration of K for groups F 50:50, F 75:25, and A 75:25, with a value of P = 0,0001. Treatments with *E. fetida* showed the highest concentrations (g/L) of N = 2,71 ± 1,10, P = 0,89 ± 0,69 and K = 4,01 ± 1,57. The importance of giving added value to the products generated during anaerobic digestion processes contributes to better yields and quality in their use and commercialization.

Keywords: biodigester, organic matter, earthworm, vermicompost

RESUMEN

La digestión anaeróbica es una tecnología utilizada en la degradación de los residuos orgánicos, con la posibilidad de obtener productos como biogás y digestatos, los cuales tienen concentraciones significativas de nutrientes. Sin embargo, usarlos sin ningún tratamiento previo puede causar varios problemas debido a la presencia de materia orgánica no estabilizada y concentraciones excesivas de nutrientes que alcanzan niveles fitotóxicos, así como la contaminación del agua y el aire. Por lo tanto, en este trabajo, presentamos un proceso de refinación de digestatos sólidos de un biodigestor alimentado con heces de oveja, mediante vermicompostaje, en combinación con desechos de plantas y utilizando lombrices de tierra de las especies *E. andrei* y *E. fetida*. Los valores de digestato al final del vermicompostaje mostraron estar dentro de los rangos óptimos de conductividad eléctrica, con valores ≤4 dS/m. Los valores de pH estuvieron entre 5,39 y 7. El porcentaje de materia orgánica estuvo entre 20 y 50 %. Se podría demostrar que el proceso de refinación aumentó la concentración de K para los grupos F 50:50, F 75:25 y A 75:25, con un valor de P = 0,0001. Los tratamientos con *E. fetida* mostraron las concentraciones (g/L) más altas de N = 2,71 ± 1,10, P = 0,89 ± 0,69 y K = 4,01 ± 1,57. La importancia de dar un valor agregado a los productos generados durante procesos de digestión anaerobia contribuye a mejores rendimientos y calidad en su uso o comercialización.

Palabras clave: biodigestor, lombriz de tierra, materia orgánica, vermicompostaje

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Introduction

Anaerobic digestion (AD) is a sustainable option in the treatment of organic waste since it takes advantage of biomass as a renewable energy source. From the AD process, mainly two products are obtained: biogas, which is used as fuel, and a stabilized residual material called 'digestate', used as a soil conditioner and/or biofertilizer for crops. The term digestate refers to the liquid-solid material obtained at the end of the AD process. Digestate resulting from this process contains a high concentration of organic matter (OM) and various plant nutrients, and it is ideal for use as a fertilizer in agriculture (Guilayn et al., 2019).

Digestate, when used incorrectly, can cause problems such as the eutrophication of water bodies (Zeng, Lemaire, Yuan, and Keller, 2003; Buosi, Pauleto, Lansac-Tôha, and Velho, 2011), groundwater contamination (Hao and Chang, 2002), and air pollution, due to the release of ammoniacal nitrogen

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(NH_3). Walker, Charles, and Cord-Ruwisch (2009) and Zeng, De Guardia, and Dabert, (2016) point out that, although the AD process provides products with a high nutrient content, which can substitute some chemical fertilizers in agriculture, their application may cause some problems:

a. The presence of biodegradable matter, which is not completely stabilized, within the digestate (Teglia, Tremier, and Martel, 2011).

b. A high concentration of NH3, which increases the nutritional value of the digestates. However, excessive concentrations lead to phytotoxic effects and generate NH_3 emissions (Ramírez, Domene, Ortiz, and Alcañiz, 2008; Nkoa, 2014).

c. The presence of pathogens that can survive up to a year, especially in mesophilic digestion systems (Appels, Baeyens, Degrève, and Dewil, 2008).

d. Difficulty when storing and transporting digestates, due to their high-water content.

Therefore, digestates must be conditioned or refined. To this effect, the main activity is to separate the digestate into two phases: liquid and solid. Tampio, Marttinen, and Rintala J. (2016) indicate that the liquid fraction has significant amounts of potassium (K) and nitrogen (N), which are soluble in water, while the solid fraction contains considerable concentrations of phosphorus (P). It is worth mentioning that the solid fraction is mostly used as an organic fertilizer, in order to obtain valuable and better marketable end products, both in traditional and ornamental agriculture (Holm-Nielsen, Al Seadi, and Oleskowicz-Popiel, 2009). Still, pollutants must be eliminated through partial composting with additives at high temperatures (Kaushik and Garg, 2003). In this process, the material is aerated and stabilized, the moisture content is reduced, and the pathogens are inactivated (Yadav, Tare, and Ahammed, 2012; Yadav and Garg, 2016; Malińska, Zabochnicka-Świątek, Cáceres, and Marfà, 2016).

Due to its importance, the solid fraction of digestates has been traditionally refined through biological processes such as composting. However, traditional composting has some disadvantages, such as long durations, frequent aeration (often mechanized), and the loss of nutrients to N volatilization, due to the high temperatures it can reach (Zeng, de Guardia, Daumoin, and Benoist, 2012; Wang, Selvam, Chan, and Wong, 2013). Instead, organic wastes can also be recycled by a wide variety of soil organisms such as bacteria, fungi, and invertebrates such as earthworms (Oyedele, Schjønning, and Amusan, 2006). The decomposition of complex organic materials into simpler and more assimilable substances (humus), and without odors derived from the action of macroorganisms (i.e. earthworms), is called 'vermicomposting'. Domínguez and Pérez-Losada (2010) define it as an accelerated process of bio-oxidation and stabilization of organic waste that is based on the interaction between earthworms and microorganisms.

Domínguez and Pérez-Losada (2010) indicate that earthworms have been used in vermicompost due to their high capacity to colonize organic waste, its high consumption, rapid digestion, and assimilation of OM, high reproducibility and its ability to tolerate a wide range of environmental conditions. Domínguez, Aira, and Gómez-Brandón (2010) describe that the vermicomposting process can be divided into two phases: (1) The direct operation phase where earth-worms process organic materials through ingestion, digestion, and assimilation, modifying the physicochemical properties and the microbial profiles of the medium; and (2) the indirect operation phase, in which microorganisms that can coexist and/or spread favorably by virtue of the existence of earthworms.

There are two highly important species: *Eisenia fetida*, and *Eisenia andrei*, which have been the most used in organic waste biodegradation (Domínguez et al., 2010). However, the application of vermicomposting has precedents, so there are control indicator parameters with established values or ranges, which favor its application in unconventional materials such as digestates. Huang, Li, Wei, Fu, and Chen (2014) report a pH stability in fruit and vegetable waste during the vermicomposting process, with initial and final values of 4,9 and 7,3, respectively, as well as the stabilization of electrical conductivity, which ranges from 1,7 to 7,1 dS/m. Norbu (2002) reports that vermicomposting reduced the OM content in municipal waste by 19,11%, 7,3% more than traditional composting. Santamaría and Ferrera (2002) concluded that the growth of *E. andrei* in different combinations of sheep feces increases from 0,23 g per individual at the beginning, to 0,49 g per individual at the end of the process, in addition to a reproduction capacity of 1 244%, regarding the sowing of earthworms, after 4 months of process. Durán and Henríquez (2009) reported the use of *E. fetida* in coffee degradation, cattle manure, household waste, banana production waste, and ornamental plant waste. The initial weight per individual was 0,37 g, and the final, up to 0,66g per individual, with a population increase of 2 816%, compared to the beginning.

Vermicompost, unlike compost, has more humidified and stable organic compounds, and its fertilizing effect is based on the slower release of nutrients that have higher concentrations of growth regulators, which have a positive effect on plant development (Jack and Thies, 2006). Vermicomposting of processed sewage sludge has shown higher N and P concentrations in comparison with traditional composting (Hait and Tare, 2011, 2012; Hanc and Dreslova, 2016). Another criticism of digestate composting is the obtaining of a heterogeneous final product (Kim, Ahn, and Speece, 2002). It has been shown that finer composts release more N and P than coarse compost (Duong, Penfold, and Marschner, 2012). Hanc and Dreslova (2016) report that vermicomposting achieves a finer and more homogeneous final product compared to classical composting. This indicates that, in general, the quality of vermicomposting is better (Sinha, Agarwal, Chauhan, and Valani, 2010).

Agricultural sectors, such as nurseries, which do not use large tracts of soil, require substrates with physical and physicochemical properties that meet production needs,

making frequent use of peat, agrolita, and compost, with higher costs (Bustamante et al., 2008; Moral, Paredes, Bustamante, Marhuenda-Egea, and Bernal, 2009). In Mexico, norm NMX-FF-109-SCFI-2008 (Secretaría de Economía, 2008) establishes the quality specifications that any earthworm humus that is produced or sold must meet. Thus, the objectives of this work were: 1) To study the feasibility of recycling and treating the solid phase of a digestate obtained from the AD of sheep feces, through vermicomposting with *E. fetida* and *E. Andrei*; and 2) to evaluate the final characteristics and value-added properties of the obtained vermicompost, taking the above-mentioned Mexican norm as reference.

Method

Obtaining digestate

The digestate came from an anaerobic digester installed in a cattle sheep ranch located in the municipality of Jalapa, Tabasco, Mexico. Only the solid fraction of the digestates was used.

Organisms

Earthworms of the species *E. andrei* and *E. fetida* were used. The organisms were taken from the vermicomposting area of the Waste Collection and Treatment Center (CATRE) of the Academic Division of Biological Sciences (DACBiol) of the Universidad Juárez Autónoma de Tabasco (UJAT) where the treatment of vegetable waste from coffee shops is carried out.

Assembly of experimental units

Sludge processing was carried out in experimental units (EU) consisting of 19 L plastic containers, each containing 5 kg of different digestate proportions with vegetable waste used in the vermicompost area (Table 1). The height of the material beds was 10 cm. The amount of biomass (organisms) added to each EU was 5,00 ± 0,02 g. On average, 17 individuals were used per EU. In each treatment group, any EU to which no vegetable debris or organisms were added was considered blank.

Table 1. Experimental design

Digestate (kg)	Vegetable wastes (kg)	Proportions	Species	Biomass (g)	Replica
5,00	–	100	*E. fetida*		
4,50	0,50	90:10	(*F group*)		
3,75	1,25	75:25	*E. andrei*	5	3
2,50	2,50	50:50	(*A group*)		
5,00	–	Blank	–		

Source: Authors

Once a week, between 30 and 50 ml of water were added with a sprayer and mixed manually.

Monitoring

During the experimental process (9 weeks), moisture content was monitored weekly and determined by weight loss when putting 10 g of wet sample into an oven at 103 °C for 24 h, according to ASTM D-2974 (ASTM International, 2000).

$$M\,(\%)=\frac{(W_0+W_h)-(W_0+W_{hd})}{(W_0+W_1)-W_0}*100$$

Where:

- $M(\%)$: moisture (%)
- W_0: weight of the container (g)
- W_1: wet weight of the material (g)
- W_h: weight of the container plus the wet weight of the earthworm humus (g)
- W_{hd}: weight of the container plus dry weight of the earthworm humus (g)

Similarly, the percentage of OM was determined by calcinating volatile solids at 550 °C for 2 h (Zagal and Zadzwaka, 2007). The solids obtained during moisture determination were used in this procedure.

$$OM(\%)=\frac{PW-PWC}{\text{sample}\,(g)}*100$$

Where:

- $OM(\%)$: percentage of $OM(\%)$
- PWC: crucible weight with calcined sample (g)
- PW: crucible weight (g)

Every 10 days, parameters such as pH and electrical conductivity (EC) were monitored. Extracts were made in water, using 10 g of the dried sample at 103 °C, and diluted in 90 ml of distilled water. This mixture was stirred for 10 min and reposed for other 30. A supernatant was taken to finally obtain extracts that were analyzed with multiparameter equipment (HANNA® HI9828).

Nutrients

At the end of the experimental process, the nutritional contents of N, P, and K were determined with photometric equipment (HANNA® HI83225).

Apparent density

Apparent density (AD) was determined by using a 100 ml graduated cylinder, which was filled with the material previously dried and sieved in a 5 µm mesh. A rubber stopper was placed and hit 3 times on a flannel to avoid damaging the container. The difference in volume by compaction was again filled, until it reached reaching 100 ml. The full specimen

was weighed, and the density calculated with the following equation:

$$AD = \frac{W}{V}$$

Where:

- AD : apparent density (g/ml)
- W : Container weight (g)
- V : Volume of the container (mL)

Biomass growth

At the end of the experiment, the organisms were counted and weighed to determine the amount of biomass obtained from each species, according to the initial values.

Statistical analysis

All obtained results were evaluated by one-way variance analysis (ANOVA) and Tukey tests with the STATGRAPHICS® Centurion XV.2 statistical package.

Results and discussion

The solid fraction was extracted manually and placed in sanitary registry with a false background to drain the most water (Figure 1 (a, b)). The organisms used were obtained from an organic waste vermicomposting process (Figure 1 (c, d)). EU assembly is shown in Figure 1 (e, f).

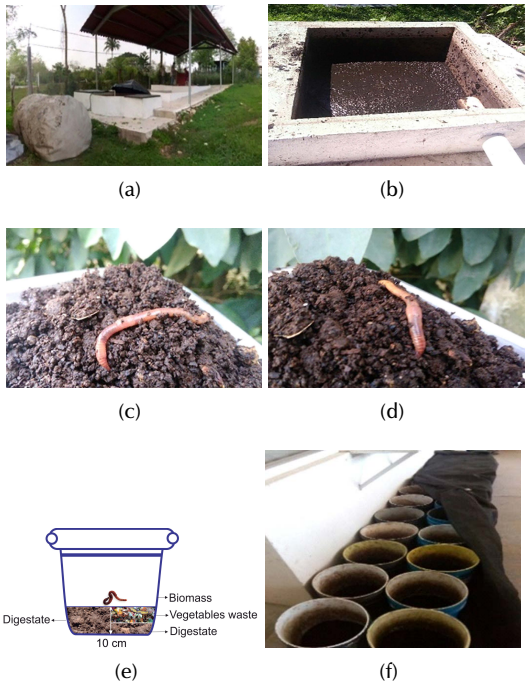

Figure 1. a) Biodigester installation; b) solid fraction of the digestates; c) *E. andrei* and d) *E. fetida*; e, f) EU assembly.
Source: Authors

The behavior of the moisture values is shown in Figure 2.

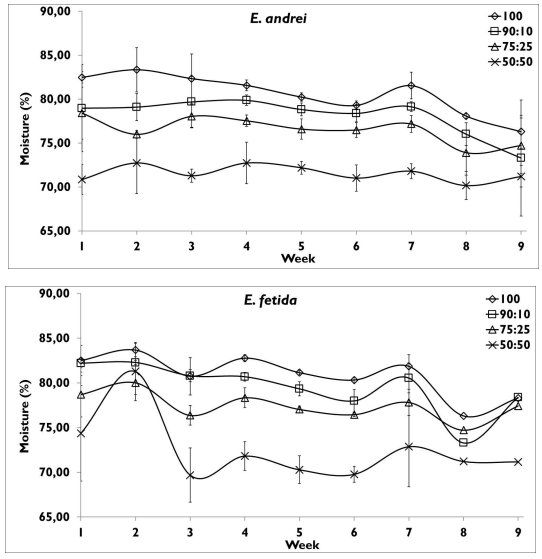

Figure 2. Moisture percent behavior in EUs with *E. andrei* and *E. fetida*.
Source: Authors

Treatments with *E. andrei* species were maintained within a range of 70 to 75% humidity, with slight decreases at the end of the process. Treatments with *E. fetida* were kept in a slightly higher range, from 75 to 80% humidity, except for the 50:50 treatment, which presented a value close to 70%. In general, moisture content was adequate during vermicomposting, which confirms what was reported by Vargas-Machuca, Romero, and Férnandez, (2014), who indicate that a minimum 70% humidity is required.

The behavior of the OM percentage is presented in Figure 3, and its final values in Table 2.

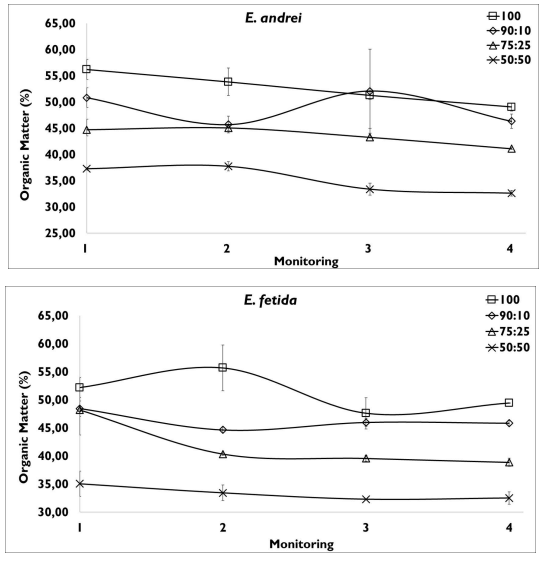

Figure 3. Behavior of OM percentage in the EUs with *E. andrei* and *E. fetida*.
Source: Authors

Table 2. Final values of the percentage of MO for each treatment

Treatment	*E. andrei*			*E. fetida*		
	Starting (g/kg)	Final (g/kg)	Loss (%)	Starting (g/kg)	Final (g/kg)	Loss (%)
100	562,20	490,50	12,75	522,10	494,40	5,30
90:10	508,30	463,50	8,81	484,40	458,50	5,35
75:25	447,10	411,10	8,05	482,10	388,70	19,37
50:50	372,90	326,30	12,50	350,60	325,20	7,24

Source: Authors

OM values in treatments with both species ranged from 35 to 58%, and a decrease was evident in all of them. *E. andrei* reached the highest removal rates: 12,75 and 12,50% in extreme treatments 100 and 50:50, respectively. This behavior can be attributed to the voracity of the species and its ease of adaptation to the environment. In treatments with the *E. fetida*, the decrease was more pronounced in treatments 75:25 and 50:50, with rates of 19,37 and 7,24%, respectively.

This is due to the traditional use of this species in the degradation of plant material, mainly in the easy metabolism of carbohydrates. Finally, the OM content of all the treatments was between 35 and 50%, which allowed them to meet the requirements of NMX-FF-109-SCFI-2008 (Secretaría de Economía, 2008) which requires a range from 20 to 50%.

In Table 3, the number and weight of the individuals at the end of the vermicomposting process are shown.

Table 3. Reproduction and growth of organisms by treatment

Treat.	*E. andrei*			*E. fetida*		
	Number	Weight (g)	Individual weight (g)	Number	Weight (g)	individual weight (g)
100	223	21,4	0,10	227	21,87	0,10
90:10:00	230	21,77	0,09	308	17,8	0,06
75:25:00	303	26,13	0,09	427	25,73	0,06
50:50:00	304	20,9	0,07	403	20,39	0,05

Source: Authors

An increase from 230% to 250% in the initial population was noticed, especially in treatments F 75:25 and F 50:50. However, the values are lower than the population increase reported by Santamaría Romero and Ferrera Cerrato (2002), as well as by Durán and Henríquez (2009). It is worth noting that the weight of the biomass was 4,1% greater in treatments with *E. andrei*. Considering the weight of the biomass divided by the number of individuals, the weight per individual was 26,14% higher in *E. andrei* compared to *E. fetida*. Both the growth and reproduction of organisms were noticeable in this work. It is probable that a higher number of organisms at the beginning and a longer processing time could have achieved higher reproduction rates.

The behavior of the pH values during the process is observed in Figure 4. It shows the final average values.

The final pH values in the treatments with the *E. andrei* were between 5,39 and 6,91, whereas, with *E. fetida,* they were

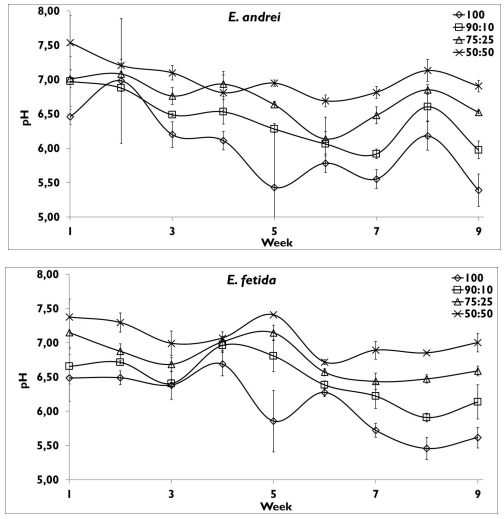

Figure 4. Behavior of pH in EU's with the species *E. andrei* and *E. fetida*.
Source: Authors

between 5,62 and 7,00. It was possible to observe that a higher presence of digestate in the treatments decreases the pH values. This can be attributed to a higher concentration of volatile fatty acids, as mentioned by Teglia et al. (2011). The final pH values of the 50:50 treatments for both species match the ones reported by Huang et al. (2014), who saw pH values of 7,3. However, despite the decrease in pH in treatments with a higher OM content, the elimination, growth, and development of organisms were not inhibited. Finally, the NMX-FF-109-SCFI-2008 (Secretaría de Economía, 2008) indicates that the final pH values should be between 5,5 and 8,5 which places the ones from the present study within the range.

The behavior of electrical conductivity is shown in Figure 5.

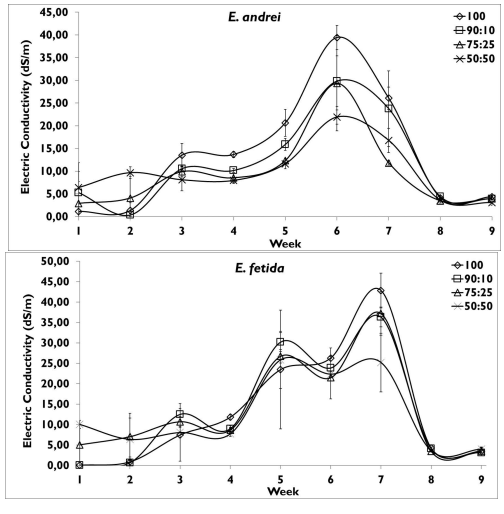

Figure 5. Behavior of electrical conductivity in EUs with the species *E. andrei* and *E. fetida*.
Source: Authors

The initial EC ranges were 1,13 - 6,4 dS/m and 0,14 - 10 dS/m for *E. andrei*, and *E. fetida*, respectively. In the end,

the EC ranges were more stable, with 3,11 - 4,37 dS/m and 3,12 - 3,99 dS/m in both species. However, the values were much higher than those reported by Huang et al. (2014). A very pronounced increase was observed in weeks 5 to 7 and there is one explanation: the EUs did not have an exit for excess liquid, the salts and minerals were concentrated in the bottom, and an inhomogeneous mixture when taking samples for analysis allowed said variation. However, the final EC values remained below the 4 dS/m established by NMX-FF-109-SCFI-2008 (Secretaría de Economía, 2008), except for the 100% treatment with *E. andrei* (4,37±0,21 dS/m).

In Table 4, nutrient concentrations are shown for each species.

Table 4. Nutrient values at the end of the process

Treat.	*E. andrei*			*E. fetida*		
	N (g/L)	P (g/L)	K (g/L)	N (g/L)	P (g/L)	K (g/L)
100	1,78±0,28	0,32±0,11	1,94±0,11	2,71±1,11	0,83±0,75	1,94±0,24
90:10	1,65±0,78	0,30±0,08	0,31±0,09	2,33±0,54	0,89±0,69	1,80±0,24
75:25	1,37±0,56	0,49±0,35	0,50±0,35	0,59±0,36	0,64±0,18	3,04±0,63
50:50	1,81±0,23	0,86±0,48	0,86±0,48	1,63±1,49	0,73±0,48	4,01±1,57
Blank*	1,63±0,62*	0,64±0,31*	0,64±0,31*	*	*	*

*Blank: the values are respective for both species.

Source: Authors

The values highlighted in Table 4 indicate the maximum values obtained for each class of nutrients. The concentrations of N in the treatments with both species were higher than in the blank. This effect was also observed in the concentration of P and K in the treatments with *E. fetida*. Therefore, these results contribute to what was mentioned by Hait and Tare (2011, 2012), Duong et al. (2012), and Hanc and Dreslova (2016), who report increases in the values of N and P in vermicomposting compared to traditional composting. Furthermore, in this work, a pre-composting process was not carried out as indicated by Kaushik and Garg (2003). Thus, it is evident that there was no loss of N due to volatilization, as reported by Zeng et al. (2012) and Wang et al. (2013). The results obtained differ from those reported by Holm-Nielsen et al. (2009), since vermicomposting not only showed high values of P, but there were also significant and higher values of N and K.

However, the one-way analysis of variance (ANOVA), performed on the obtained N and P values did not show statistically significant differences, with values of P = 0,1306 and 0,2192, respectively. Still, in the ANOVA of K, a value of P = 0,0001 was obtained, which indicates highly significant statistical differences between the treatments (Figure 6).

With a multiple range contrast test (Tukey) and a Matt-Whitney test, it was determined that treatments F 50:50, F 75:25, and A 75:25, had the highest concentrations of K in comparison with the other treatments, as seen in Figure 6. Equal letters mean similarity between groups, but all treatments tend to be older than the witness treatments.

The final values of apparent density are shown in Table 5.

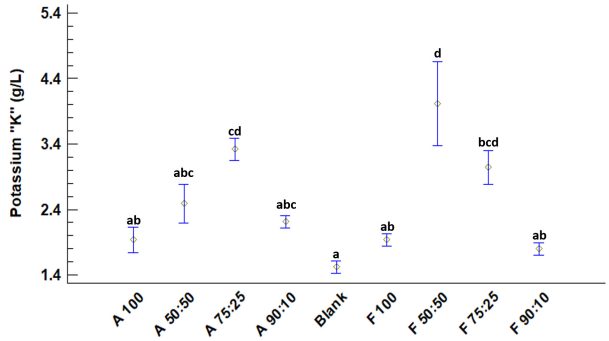

Figure 6. Analysis of variance with standard error.
Source: Authors

Table 5. Bulk density values at the end of the process

Treatment	*E. andrei* (g/ml)	*E. fetida* (g/ml)
100	0,51	0,49
90:10	0,53	0,49
75:25	0,55	0,53
50:50	0,59	0,57
Blank	0,42	–

Source: Authors

All obtained values were within the range established by NMX-FF-109-SCFI-2008 (Secretaría de Economía, 2008): from 0,40 to 0,90 g/ml. There is a trending increase in apparent density, with respect to the increase in the proportions of the treatments. This trend can be interpreted as a better particle size homogeneity, where a finer product is compared to blank values, thus contributing to the reports by Kim et al. (2002) and Hanc and Dreslova (2016).

Conclusions

The viability of the vermicomposting process in the refining of the solid fraction of digestates has demonstrated a stabilization in physicochemical parameters. The quality of the final product meets most of the established parameters in the Mexican standard. The species *E. andrei* presented values close to the upper limit of the regulated ranges, fulfilling 80% of the measured variables. Therefore, it can concluded that this species are considered more suitable for use in this process, especially since it has a higher OM removal capacity. The use of *E. fetida* has a greater capacity for reproduction and growth, as well as a higher concentration of nutrients, particularly K. However, this species offers a slightly similar concentration of K, with a higher proportion of digestates and fewer plant residues. The effect of pH variation allows us to generate two hypotheses:

1. There was a presence of VFA, resulting in a greater presence of digestates that caused lower pH levels;
2. and the final humidity was affected, since the treatments with higher humidity (*E. fetida*) showed a slight increase in pH, and treatments with lower moisture content (*E. andrei*) had lower pH values.

Finally, it is important to expand this research in the field of microbiology, such as how to study pathogens, digestive capacity, the presence of heavy and toxic metals, and the feasibility of applying the final product in crops on a pilot scale.

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Biorefinery Concept Applied to Phytochemical Extraction and Bio-Syngas Production using Agro-Industrial Waste Biomass: A Review

Concepto de biorrefinería aplicado a la extracción fitoquímica y producción de bio-singas usando biomasa de residuos agro-industriales: una revisión

Carlos Esteban Aristizábal-Alzate[1], Pedro Nel Alvarado[2], and Andrés Felipe Vargas[3]

ABSTRACT

Second-generation biomass is a renewable resource that can address the increasing global energy demand and help to partially substitute the use of and dependence on fossil fuels, since it can be transformed into gas, liquid and/or solid fuels by physical, thermal, thermochemical and/or biological processes. However, its potential is not fully exploited because the process to extract the phytochemicals present in such organic byproducts has been largely omitted. Natural compounds are of interest to high value-added industries such as cosmetics and pharmaceutics. Therefore, this work proposes to thoroughly use such residual biomass in a biorefinery by a simultaneous, efficient and sustainable integration and operation of extraction processes to obtain phytochemicals and functional extracts. A thermochemical process known as gasification is implemented to produce syngas, which can be turned into fuels, chemicals, and energy such as methanol and synthetic gasoline. Furthermore, this review article describes the state of the art of each process and the concept of biorefinery.

Keywords: biorefinery, waste biomass, thermochemical conversion, bio-syngas, phytochemical extraction

RESUMEN

La biomasa de segunda generación es un recurso renovable que puede abordar la creciente demanda mundial de energía y ayudar a sustituir parcialmente el uso y la dependencia de los combustibles fósiles, ya que puede transformarse en gas, líquidos y/o combustibles sólidos por medio de procesos físicos, térmicos, termoquímicos y/o biológicos. Sin embargo, su potencial no se explota completamente porque no se considera el proceso de extracción de los fitoquímicos presentes en dichos subproductos orgánicos. Los compuestos naturales son de interés para las industrias de alto valor agregado como la cosmética y la farmacéutica. Por lo tanto, este trabajo propone utilizar a fondo dicha biomasa residual en una biorrefinería mediante una integración y operación simultánea, eficiente y sostenible de los procesos de extracción para obtener fitoquímicos y extractos funcionales. Se implementa un proceso termoquímico conocido como gasificación para producir gas de síntesis, que puede convertirse en combustibles, productos químicos y energía tales como metanol y gasolinas sintéticas. Además, este artículo de revisión describe el estado del arte de cada proceso y el concepto de biorrefinería.

Palabras clave: biorrefinería, biomasa residual, conversión termoquímica, syngas, extracción fitoquímica

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Introduction

Nowadays, first-generation biomass is commonly used to obtain biofuels in order to address the increasing global energy demand and partially substitute fossil fuels. For example, vegetable oils from oil palm plantations or rapeseed in Europe are employed to produce biodiesel, and plants rich in fermentable sugars such as corn, cereals, and sugarcane are processed to produce bioethanol (Jin, Yang, Poe, and Huang, 2018; Kajaste, 2014; Ubando, Felix, and Chen, 2020). However, the exploitation of this type of biomass entails a problem, since it competes for the use of land and, in traditional agriculture, these products are feedstock, which increases and volatilizes their price (Damartzis and Zabaniotou, 2011; Lapkin et al., 2014). Besides, we live in an era of human dominance that has altered biogeochemical carbon, nitrogen, phosphorus, and water cycles (Carey,

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Yang, McNamara, and Mayer, 2016) and affected agricultural productivity, as well as the quality and fertility of the soil.

The most widely-recommended raw material to produce different types of high value-added products is second-generation biomass (2G). These include the more affordable and widely available lignocellulosic residues from agro-industrial activities. If 2G is not valorized, it will often be disposed of in sanitary landfills, used like a low quality fuel, or returned to the field as a fertilizer (Löffler et al., 2010; Zondervan, Nawaz, de Haan, Woodley, and Gani, 2011). As a result, the production costs of fuels and/or chemicals obtained from it are lower than those from first-generation biomass or energy crops (Bentsen, Felby, and Thorsen, 2014; Damartzis and Zabaniotou, 2011; Demirbas, 2010a; Ekman, Wallberg, Joelsson, and Börjesson, 2013). Additionally, this type of biomass does not have the same problems of its first-generation counterpart, since it is nonedible (Ubando et al., 2020).

This type of recovery is carried out at facilities known as biorefineries, which provide a conversion process with different products (energy, food/fodder, materials, chemicals, etc.) with ideally zero waste production (Carey et al., 2016; Martinez, Kok, and Ng, 2018; Ubando et al., 2020). This enables the recovery of nutrients to produce fertilizers by extracting high value-added phytochemicals (e.g., caffeine, polyphenols, and saponins, etc.) (Carey et al., 2016; Esquivel and Jiménez, 2012; Murthy and Madhava Naidu, 2012). Such waste is later used as a source of electrical energy, fuel, and/or chemicals in general (methanol) by means of a thermochemical treatment (gasification). In Colombia, a few industries have adopted this concept and recover this type of active or functional principles because their content in vegetable raw material is relatively low (Lapkin et al., 2014). Furthermore, if the energy in second-generation biomass, which is not efficiently recovered to make other functional products, given that it is generally employed as fertilizer or low-quality fuel (Bilhat Chala, Sajid Latif, 2015; Lapkin et al., 2014; Salinas Rios et al., 2014; Torres-Mancera et al., 2011), all its potential for adding value is wasted and it becomes an environmental issue (Hughes et al., 2014).

However, this type of facilities has to be studied in more detail, because the biomass supply chain could be noncontinuous and stable due to the fact that agro-industrial wastes are usually collected after the harvesting agricultural crops, and many of them have a seasonality nature, which affects the logistics and operation of the biorefinery. Therefore, the challenge is to manage biomass availability and storage in order to maintain a continuous *in situ* operation and production (Yue et al., 2014).

Biomass

First, it should be clarified that biomass is any organic material that can constitute the main raw material of a biorefinery, and it is classified into four types according to its origin (Maity, 2015):

I. Energy crops (corn, sugarcane, oil palm, etc.)

II. Agro-industrial waste (palm kernel, coffee pulp, etc.)

III. Wastes from tree pruning, gardening, etc.

IV. Municipal and industrial waste

Second-generation or type II biomass is a renewable source of energy and it corresponds to the biodegradable fraction of products, wastes and residues of agriculture, forestry, cattle raising and related industries, as well as the above-mentioned fraction of municipal and industrial wastes (Bentsen et al., 2014; Löffler et al., 2010; Martinez et al., 2018). Additionally, biomass is the only renewable resource that can be transformed into gas, liquid and/or solid fuels by physical, thermal, thermochemical and/or biological processes (see Figure 1) (Balagurumurthy, Singh, Ohri, and Prakash, 2015; Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, and Duarte Ortega, 2010; ISAGEN, 2005).

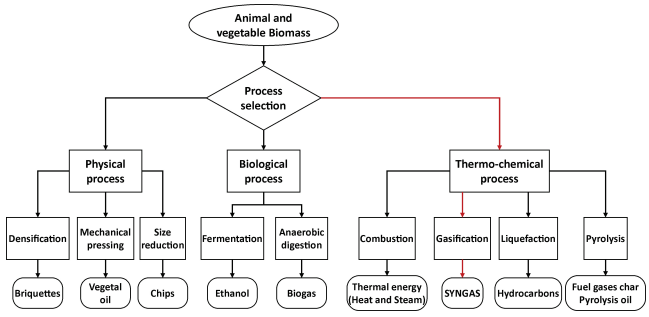

Figure 1. Energy recovery processes.
Source: Authors

In Colombia, there are many sources of residual biomass as a result of its agricultural vocation (Escalante Hernández et al., 2010; Hernández A., 1994) and the amount of agro-industrial waste from crops are of great socioeconomic importance in the country (see Figure 2). Such waste can be turned into a great opportunity to generate high value-added chemicals and/or electrical energy (Ekman et al., 2013).

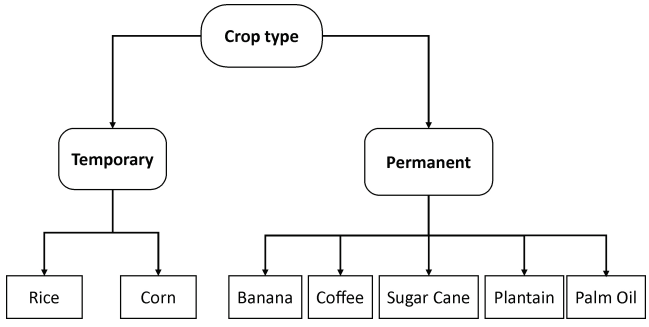

Figure 2. Crops that generate waste biomass in Colombia.
Source: Authors

These agro-industrial wastes are based on organic polymers such as lignin and cellulose. Due to a structure composed of

carbohydrate chains, this kind of biomass is highly oxygenated in comparison with conventional fossil fuels, including liquid hydrocarbons and carbon. Nevertheless, its main constituent is carbon (Virmond, Rocha, Moreira, and José, 2013). Even though this renewable resource employed as raw material to produce energy, chemicals, and fuels will not satisfy humanity's needs in the short term, it will open the possibility of being a more sustainable and environmentally-friendly society through the concept of biorefineries (Clark, 2007).

Biorefineries

This type of facility is firmly based on the principles of sustainable use of land and green raw materials, environmentally-friendly technologies, and energy self-sufficiency, among others (Gil-Montenegro, Arocha-Morales, Rojas-Pérez, and Narváez-Rincón, 2019; Kamm, Schönicke, and Hille, 2016). It can transform biomass and/or biologic materials into fuels, chemicals, pharmaceutics, energy, and even food and animal feed (Demirbas, 2009, 2010b; Ekman et al., 2013; Kamm et al., 2016; Löffler et al., 2010) (see Figure 3). These multiproduct platforms are designed and operated embracing the previously described sustainability principles and considering the features of the biomass, the sub products, and final products in terms of biochemical and chemical composition in order to find the best technologies and/or conversion routes that generate the most added value, profitability, and the least negative impact on the environment (Kamm et al., 2016; Maity, 2015).

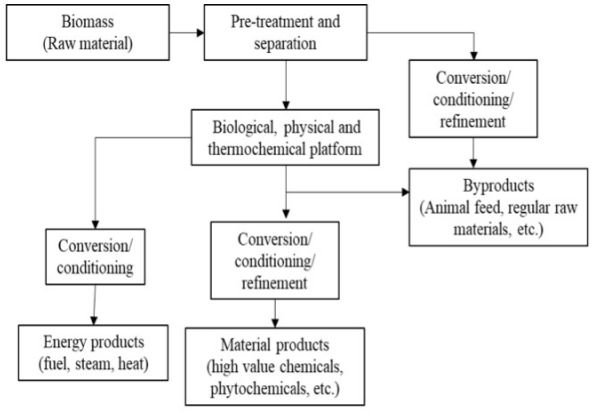

Figure 3. Scheme of the operation of a biorefinery.
Source: Authors

Although Figure 3 and Table 1 describe several types of biorefineries, the differences between them are the type of treatment or conversion route that the biomass follows (thermal, biological or chemical), the production technologies, the characteristics of the raw materials, and their final products (Demirbas, 2009, 2010b; Kamm and Kamm, 2004; Löffler et al., 2010). Particularly, biorefineries that convert biomass into fuels, high value-added chemicals, electricity, and heat can generally be divided into two types: thermochemical and biological (Joglekar, Pathak, and Mandavgane, 2019; Parajuli et al., 2015). Thus, the types of biorefinery and the associated products are shown in Table 1.

Table 1. Classification of biorefineries according to their conversion route

Biorefinery	Path	Products
Biosyngas-based	Thermochemical	Syngas, hydrogen, methanol, dimethyl ether, diesel (Fischer-Tropsch)
Pyrolysis-based	Thermochemical	Bio-oils, fuels, diesel, and hydrogen, among others
Hydrothermal reforming	Thermochemical	Hydrocarbon compounds, chemicals, diesel and fuels
Fermentation-based	Biological	Bioethanol
Oil from vegetable species	Chemical	Biodiesel, diesel, and gasoline

Source: Demirbas, 2010b

The operation, functionality, and characteristics of a biorefinery are usually compared to those of an oil refinery (Ariel, Alzate, Camilo, Toro, and Peña, 2018; Carey et al., 2016; Maity, 2014) because they work in a similar way, and a great portion of the products obtained from this fossil material, or their substitutes, can be manufactured from biomass (Kamm and Kamm, 2004; Kamm et al., 2016; Löffler et al., 2010). However, the most important difference is that oil refineries use a non-renewable resource (petroleum), while biorefineries use a renewable option (biomass) (Ariel et al., 2018; Carey et al., 2016; Haro, Ollero, Perales, and Vidal-Barrero, 2013).

Currently, there is another concept or industry like a biorefinery that seeks to mitigate environmental damage and use resources in a sustainable and rational way: polygeneration. Using this concept enables producing power and high-quality, high value-added chemical products through the efficient transformation of mainly non-renewable natural resources, such as carbon or natural gas. Therefore, this type of systems and biorefineries is considered to be the future of chemical and electrical power generation industries (Gangadharan, Zanwar, Zheng, Gossage, and Lou, 2012; Löffler et al., 2010).

The possibility of making a wide range of products greatly depends on the availability and characteristics of the biomass, its chemical composition of raw materials, and the technologies used for their transformation and energy recovery (Ekman et al., 2013; Maity, 2015; Zondervan et al., 2011). Industries that can apply several technologies and processes to transform a raw material (carbon and natural gas for polygeneration plants and biomass for biorefineries) provide a greater economic profit, rational and optimal use of resources, higher energy efficiency, less polluting emissions, and less negative effects on the environment (Kachrimanidou et al., 2015). To enjoy these benefits,

the optimal operating conditions of a plant have to be carefully determined. Nevertheless, these conditions or operating parameters must not be generalized, because this type of facilities should be planned and adjusted to economic characteristics related to the market, the availability of resources, and the features of the raw materials associated with the plant's location (Demirbas, 2009; Leduc, Lundgren, Franklin, and Dotzauer, 2010; Löffler et al., 2010).)

Some literature and studies try to formulate, plan, and determine the best operating conditions for a plant that manufactures several types of products from renewable and non-renewable sources by simulating chemical processes and generating mathematical models and sensitivity analyses. These works try to model the operation of a plant in different situations. In general, they change market prices of raw materials, products, technologies and transformation. The operating parameters obtained from the development and solution of the models and simulations aim to guarantee the economic sustainability of the plant (Buragohain, Mahanta, and Moholkar, 2010b; Demirbas, 2009; Ekman et al., 2013; Zondervan et al., 2011). In some cases, they also minimize negative effects on the environment and the society (Gangadharan et al., 2012; Ng, Andiappan, Chemmangattuvalappil, and Ng, 2015).

Although plants or facilities of this kind have been widely studied in economic terms (Ng et al., 2015), their flexibility and capacity to respond to external disturbances have not been examined (Meerman, Ramírez, Turkenburg, and Faaij, 2012; Ngan et al., 2020; Sadhukhan et al., 2018). Furthermore, the economic and environmental costs of conventional technologies to manufacture a certain product are not usually compared to those of a novel alternative such as biorefineries. This is the case of a work that reports that the efficient energy recovery of nitrogen from a source of waste biomass at a biorefinery could reduce the existing dependence on the Haber-Bosch process, which uses between 1 and 2% of the total energy consumed world-wide (Carey et al., 2016). Thus, it avoids the consumption of natural resources, energy, and emissions harmful to human health that are associated with this process, which enables to obtain the fixed nitrogen needed to fertilize soils devoted to agriculture. Additionally, there is a considerable number of articles that deal with energy recovery from second-generation biomass under the concept of biorefinery. Nevertheless, they have not extensively discussed or considered the possibility of extracting high value-added biochemical and phytochemicals form raw biomass and, at the same time, produce fuels, electricity, and chemicals in general (Folmer, 2014; Lapkin et al., 2014), as can be confirmed in the work by Hughes et al. (2014).

Since Colombia is an agricultural country, the implementation of this type of concepts and methods entails a great challenge and opportunity for sustainable development, since niche markets such as pharmaceutics and cosmetics demand novel, functional, efficient, natural, and/or biobased ingredients (Departamento Nacional de Planeación DNP-DDRS Ministerio de Agricultura y Desarrollo Rural, Ministerio de Ambiente, Vivienda y Desarrollo Territorial Ministerio de Comercio, Social, Exteriores, and Colciencias, 2011; Parajuli et al., 2015). The global market of special biochemical products (e.g., enzymes, flavors and fragrances, biopesticides, thickening agents, plant growth promotors, essential amino acids, and vitamins) based on biomass currently amounts to several billion US dollars per year, and it grows from 10 to 20% annually (Parajuli et al., 2015).

Phytochemical extraction and production of high value-added chemicals

There are two types of metabolites in biomass: primary and secondary. The first kind includes macromolecular compounds, such as polysaccharides (lignin and cellulose); the second (low-content) consists of waxes, oils, terpenes, and sterols. These components are highly relevant in biorefineries because they are functional and, in many cases, present biological activity (Clark et al., 2006; Herrero and Ibañez, 2018; Moncada, Aristizábal, and Cardona, 2016).

The extraction of secondary metabolites and the manufacture of natural products are gaining traction in the food, cosmetics, and pharmaceutical industries because final consumers are increasingly interested in biobased products of organic and sustainable nature that embrace the principles of green chemistry (Bergs et al., 2013; Herrero and Ibañez, 2018; Hughes et al., 2014). Moreover, the current trend in the field of profitable and sustainable recovery of waste biomass from agro-industrial processes (e.g., the coffee agroindustry) is exploiting the bioactive fractions and/or precursors of chemical compounds of general interest such as polyphenols, lipids, and carbohydrates, thus generating added value throughout the production chain (Ariel et al., 2087; Burniol-figols, Cenian, Skiadas, and Gavala, 2016). Figure 4 presents the block diagram of a proposed biorefinery that includes phytochemical extraction in the operation.

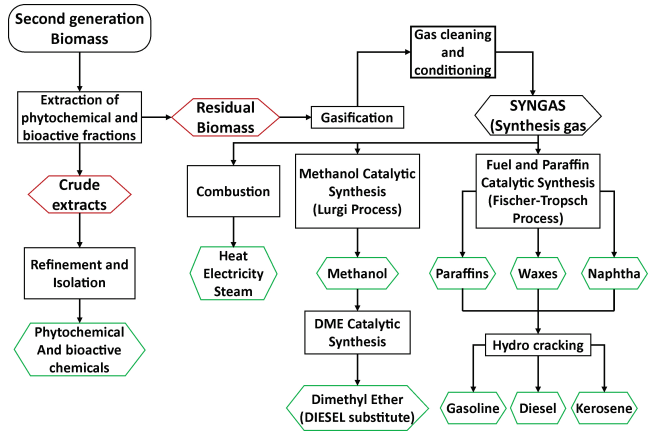

Figure 4. Scheme of the operation of a biorefinery.
Source: Authors

Biorefineries usually transform the entire biomass into fuels or plattform chemicals, and do not take advantage of secondary metabolites. In Figure 4, a proposed biorefinery is shown. It considers a novel procedure: phytochemical extraction prior to the thermochemical processes. The main advantage is that bioactive chemicals from secondary metabolites have the best market price per weight of material, since they are employed as raw materials in high-value industries such as pharmaceutic, cosmetic or human wellness industries.

The extraction method depends on the type of biomass (Ariel et al., 2018). Therefore, to have a sustainable and profitable operation, two questions should be addressed: What is the influence of the conditions of the process on the efficiency of the sequential or direct extraction of the target chemical fractions? And how does the scale of the process affect its performance? (Trivedi et al., 2016).

There are many well-known extraction techniques nowadays. Some of the most popular are solid-liquid, liquid-liquid, acid-base, and ultrasound and microwave-assisted extraction (Rombaut, Tixier, Bily, and Chemat, 2014a; Segneanu, Cziple, and Vlazan, 2013). Other techniques use pressurized fluids such as solvents; this is the case of supercritical fluids and pressurized liquids, among others (Herrero and Ibañez, 2018; Yeoh, Chong, Azahan, and Rahman, 2013). Nevertheless, the latter are associated with high investment costs, although, real economic evaluations of the process (including large-scale simulations) have not been carried out in most cases (Herrero and Ibañez, 2018).

In leaching extraction, the main issue is to find the most adequate solvent that enables the extraction of the phytochemicals of interest from biogenic raw material (Aristizábal-Alzate, 2016; C. E. Aristizábal, Vargas, and Alvarado, 2017; Herrero and Ibañez, 2018). However, the choice of solvents must be guided by a technical framework that includes key factors to achieve high efficiency (e.g., selectivity of the extraction, viscosity of the solvent, surface tension, cellular location of the target compound, and the part of the plant to be used as biomass (Bergs et al., 2013), among others) and observes the principles of green chemistry (Chemat, Vian, and Cravotto, 2012; Ghandi, 2014). For example, a numerical technique to select the solvent was proposed by Aristizábal (2016). It considers the Hansen solubility parameters of the secondary metabolites of interest and different solvents, as well as the affinity and the improvement of the performance of the solid-liquid extraction process. Table 2 below provides general information on some agro-industrial wastes, and the type of biorefinery that could be used to recover their energy, and possible high value-added products of industrial interest.

Biomass resulting from extraction processes is forwarded to thermochemical treatment, chemical or biological hydrolysis, and/or fermentation to obtain other high value-added chemicals (Moncada et al., 2016). Thus, byproducts are recycled, sustainability and profitability are increased, and the emission of pollutants by the biorefinery is reduced (Clark, 2007; Kajaste, 2014; Kamm et al., 2016). However, the recommendation in this case is a thermochemical process because traces of solvents used during phytochemical extraction may inhibit the growth of microorganisms, which would be counterproductive for a biological treatment (Lapkin et al., 2014). Furthermore, biofuels obtained from second-generation biomass have not been commercialized due to the low efficiencies and high costs of the equipment (Virmond et al., 2013). Besides, thermochemical methods use all components of the biomass (biodegradable and non-biodegradable fractions) without a pre-treatment stage, and they take from seconds to hours to produce hydrocarbons, value-added chemicals, and electricity, compared to biochemical processes that take days to complete the biotransformation and use microorganisms to turn the organic and biodegradable material only into alcohols and biogas by anaerobic digestion. Additionally, the slightest change in the composition of the biomass could produce functionality failures and undesired production due to changes in the metabolic route (Singh, Krishna, Mishra, Kumar, and Bhaskar, 2016). Therefore, the next section will describe thermochemical routes: gasification, methanol production, and the Fischer-Tropsch process. It can then be coupled with phytochemical extraction.

Gasification

The objective of this thermochemical treatment is to produce a mixture of CO, CO_2, H_2 and CH_4 known as syngas (Molino, Chianese, and Musmarra, 2016; Pacioni et al., 2016; Pereira, Da Silva, De Oliveira, and Machado, 2012). The chemical reactions in this process take place in an environment with a limited amount of oxygen or another kind of oxidizing agent (air, steam, and a mixture of them) (Heidenreich and Foscolo, 2015; Richardson, Drobek, Julbe, Blin, and Pinta, 2015; Ramirez Rubio, Sierra, and Guerrero, 2011). During gasification, the biomass fed to the system is partially oxidized. This endothermal process, which occurs at high temperatures (500-1400 °C) and atmospheric pressures up to 33 bar (Ahmad, Zawawi, Kasim, Inayat, and Khasri, 2016), also needs a heat supply (Molino et al., 2016). Below, Figure 5 illustrates the gasification process and its different stages. It also shows the inputs and outputs of this treatment.

The material fed to the equipment (biomass, in this case) should contain an amount of water content below 35%. Water contents between 25 and 60% directly affect the efficiency of the gasifier, which results in energy losses (Ahmad et al., 2016).

Syngas can be used for several purposes such as heat and electrical energy generation. Furthermore, synthesis gas is employed to produce fuels through the Fischer-Tropsch process, methanol through the Lurgi-Ruhrgas process, and dimethyl ether and formaldehyde (Ahmad et al., 2016; Clifford, 2015; Moncada et al., 2016; Pacioni et al., 2016). Nevertheless, the quality of Syngas should be considered when used as raw material to produce energy and/or the previously mentioned chemicals, since it is affected by several factors, conditions, and operating parameters such as:

Table 2. Agro-industrial wastes and products of industrial interest

Agro-industrial waste	Type of biorefinery	Extraction method	High value-added products	Other products of industrial interest	References
Coffee pulp, coffee bean husk, silver skin	Biosyngas-based	Hydroalcoholic solvents	Chlorogenic acid and other polyphenols, caffeine, pectins, and flavonoids	Methanol, synthetic gasolines, dimethyl-ether, and thermal energy	(Folmer, 2014; Hughes et al., 2014; Murthy and Madhava Naidu, 2012)
	Based on fermentation and/or biological processes	Supercritical water	Enzymes, fungi, and critic acid	Ethanol and biogas	
Orange peel	Biosyngas-based	Hydrodistillation Solvent-free, microwave-assisted	Limonin, pectens, and essential oils, among others	Methanol, synthetic gasolines, dimethyl-ether, and thermal energy	(Aissou, Chemat-Djenni, Yara-Varón, Fabiano-Tixier, and Chemat, 2017; Negro, Mancini, Ruggeri, and Fino, 2016), (Rombaut, Tixier, Bily, and Chemat, 2014)
Olive tree pruning waste, olives, and olive pulp	Based on fermentation and/or biological processes	Solvents and acid hydrolysis treatments Ultrasound-assisted	Polyphenols and orujo (olive waste) oil	Ethanol	(Romero-García et al., 2014)
Avocado agro-industrial waste	Based on fermentation and/or biological processes	Enhanced-Fluidity Liquid Extraction (EFLE) with CO2 and ethanol	Polyphenols and xylitol	Ethanol	(Dávila, Rosenberg, Castro, and Cardona, 2017)

Source: Authors

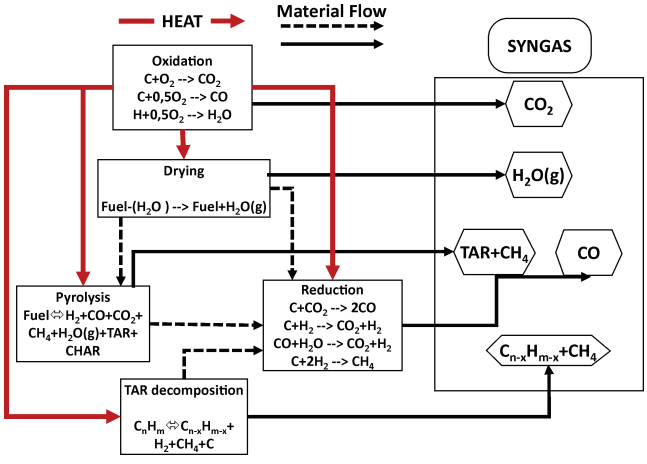

Figure 5. General scheme and areas of a gasification process.
Source: Based on (Molino et al., 2016)

i) Type of gasifier

ii) Operating temperature

iii) Particle size of the raw material

iv) Gasifying agent

Since the most desirable product is a synthesis gas rich in CO and H_2 to be used as chemical platform, temperatures in the 1200-1300 °C range allow the formation of these compounds and avoid the formation of methane. Specifically, particle sizes below 0,3 mm favor the production of CO, H_2, and CH_4, and reduce that of CO_2. However, particle sizes under 0,15 mm affect the performance of H_2 production. To select the gasifying agent, several studies demonstrated that a mixture of oxygen and vapor produces higher concentrations of CO and H_2 in the syngas (63,27-72,56%) than using air (52,19-63,31%) (Ahmad et al., 2016).

Table 3 presents, as an example, the composition of a synthesis gas obtained from the gasification of Colombian agro-industrial waste as a function of the variation of the vapor/biomass ratio. It indicates that the initial characteristics of the biomass influence the final composition of the syngas and, depending on the selection of the gasifying agent and biomass ratio, this gas can be enriched or impoverished in one or several of its constituents. For example, we can observe that, regardless of the type of biomass, when the amount of water vapor is increased with respect to the biomass, the content of hydrogen (H_2) rises and carbon monoxide (CO) falls. Therefore, special attention must be paid when the input gasification parameters are set because, depending on the final use of the syngas, they should meet a certain composition, much more so if Syngas is recovered during the catalytic synthesis of other chemical compounds.

Table 3. Comparison of syngas composition (%v/v) and its calorific value over 1,123 K (850 °C) for different vapor/biomass ratios (weight fraction)

Palm kernel	vapor/biomass	CO	CO_2	H_2	CH_4	Ho (MJ/NM3)
% dry basis	0,50	45,24	2,36	51,45	0,95	12,64
	1,00	33,32	10,40	55,30	0,98	11,64
	1,50	26,16	15,22	57,67	0,93	11,02
	2,00	21,65	18,25	59,22	0,88	10,63
Coffee silver skin	vapor/biomass	CO	CO_2	H_2	CH_4	Ho (MJ/NM3)
% dry basis	0,50	44,80	4,10	50,20	0,90	12,41
	1,00	32,97	11,97	54,14	0,91	11,42
	1,50	25,87	16,68	56,58	0,89	10,83
	2,00	21,40	19,62	58,14	0,84	10,44

Source: Garcia, 2011

There are two types of phenomenological models that theoretically describe the behavior of the gasification process. The first kind includes 1D, 2D, or 3D kinetic models (depending on the space coordinates) that predict in more detailthe phenomenon, the evolution of the species, and the thermal and dynamic state of the process in the space conditions under consideration, due to the application of chemical kinetics, the description of the transport phenomena, and the balances between matter, energy, and momentum. The second type of model is related to chemical equilibrium, which can be divided into two groups: stoichiometric and non-stoichiometric methods (Costa, La Villetta, and Massarotti, 2015; Garcia, 2011; Rodrigues, Muniz, and Marcilio, 2016). Nevertheless, the second kind requires a number of kinetic parameters, determined through experimentation, that can range from a few to thousands depending on the selected gasification equipment, operating conditions, and kind of biomass (García, 2011). The main reactions in the gasification process are illustrated in Table 4.

Table 4. Basic reactions in the gasification process. NR: Not reported

Reaction	Heat of reaction (MJ/kmol)	Name of the reaction
Heterogeneous reactions		
$C + 0{,}5O_2 \leftrightarrow CO$	-111	Char partial combustion
$C + CO_2 \leftrightarrow 2CO$	172	Boudouard reaction
$C + H_2O \leftrightarrow CO + H_2$	131	Water-gas
$C + 2H_2 \leftrightarrow CH_4$	-75	Methanation
Homogeneous reactions		
$CO + 0{,}5O_2 \leftrightarrow CO_2$	-283	Partial combustion of CO
$H_2 + 0{,}5O_2 \leftrightarrow H_2O$	-242	Partial combustion of H_2
$CO + H_2O \leftrightarrow H_2 + CO_2$	-41	Shift reaction
$CH_4 + H_2O \leftrightarrow 3H_2 + CO$	206	Vapor-methane reforming
$H_2 + S \leftrightarrow H_2S$	NR	H_2S formation
$0{,}5N_2 + 1{,}5H_2 \leftrightarrow NH_3$	NR	NH_3 formation

Source: Ahmad et al., 2016

In addition, thermodynamic equilibrium or 0D models require less information and are valuable because they can predict the thermodynamic limits of a gasification system, regardless of the type of gasifier. As a result, they are simple, adequate to study the influence of operating parameters on the composition of the syngas (Hian, Saleh, and Abdul Samad, 2016; Rodrigues et al., 2016; Ruggiero and Manfrida, 1999), but they are only valid under chemical equilibrium conditions (Rodrigues et al., 2016). Other approaches involve Neural Networks and Computational Fluid Dynamics (CFD) (Costa et al., 2015; George, Arun, and Muraleedharan, 2016; La Villetta, Costa, and Massarotti, 2017).

Syngas: chemical platform to generate added value

As previously mentioned, the goal of a biorefinery is to integrate processes in order to simultaneously produce chemicals, fuels, and electricity that generate the optimum economic benefit (Ariel et al., 2018; Parajuli et al., 2015). For that purpose, processes and technologies that ensure the plant's sustainability and versatility in the long term should be integrated by incorporating different processing units in a modular way (C. Aristizábal, 2016). The following subsections describe some of the routes selected to exploit syngas and thus generate added value from its transformation into fuels, chemicals, and/or thermal energy (Bai, Liu, Lei, Li, and Jin, 2015; Rauch, Hrbek, and Hofbauer, 2014).

Catalytic synthesis of methanol

Methanol, or methyl alcohol (CH_3OH), is one of the few chemical substances produced in megatons and traded in international commodity markets (Cooper, 2010). This alcohol is the precursor of a great variety of chemical compounds, such as formaldehyde (70%), methyl tert-butyl ether (20%), and acetic acid. It also is an excellent fuel because of its octane rating of 113, the gasoline/methanol mixture (90/10) can increase the octane number of gasoline up to 130, and the engines that work with reach an efficiency of about 43% (Bozzano and Manenti, 2016). Besides being used to produce biofuels, it holds an approximately 10% share of total raw materials involved in this process, and it can be used to manufacture dimethyl ether, a chemical compound with the potential to compete with the consumption of conventional diesel (Bansode and Urakawa, 2014; Gangadharan et al., 2012; Pontzen, Liebner, Gronemann, Rothaemel, and Ahlers, 2011). Methyl alcohol would favor the transition from fossil to natural resources (Bozzano and Manenti, 2016).

Table 5. Methanol synthesis technologies

Technology supplier	Operating temperature (°C)	Operating pressure (bar)	Notes
ICI (Synetix)	210-290	50-100	ARC, Tubular cooled isothermal Linde, and Toyo reactor
Lurgi	230-265	50-100	Tubular, isothermal reactor
Mitsubishi	235-270	50-200	Tubular, isothermal reactor
Kellog	–	–	Spherical reactor geometry
Linde AG	240-270	50-150	–
Haldor Topsøe	200-310	40-125	To this day, there are no plants in commercial operation that apply this process.

Source: Riaz, Zahedi, and Klemeš, 2013

Methanol can be manufactured through the catalytic reaction between CO, H_2, and CO_2 (Cooper, 2010). The conventional processes to produce this substance from synthesis gas or syngas are carried out in a multitubular fixed-bed reactor with a pellet-shaped Cu-ZnO-Al2O3 catalyst operating in gas phase (Hamelinck and Faaij, 2002; Holmgren, Berntsson, Andersson, and Rydberg, 2012; Leduc et al., 2010; Narvaez, Chadwick, and Kershenbaum, 2014). As this is a highly exothermal process, a cooling system should be

implemented because high temperatures affect the useful life of the catalyst and, therefore, the reactor's performance. Table 5 below presents the main suppliers of methanol synthesis technologies and their operating conditions.

The equipment that produces methanol is fed syngas with a 2:1 ratio of hydrogen to carbon monoxide (Gangadharan et al., 2012; Gao et al., 2008; Holmgren et al., 2012). In addition, two other chemical pathways take place to generate methanol: either the CO_2 reacts with hydrogen to form methanol and water, or there is a shift reaction (see Table 6).

Table 6. Chemical reactions and equations of the methanol production process

Description of the chemical reaction	Chemical equation
Main reaction in the process of obtaining methanol from syngas	$CO + 2H_2 \rightarrow CH_3OH$
Carbon dioxide reaction in the methanol reactor	$CO2 + 3H_2 \rightarrow CH_3OH + H_2O$
Shift reaction inside the methanol reactor	$CO + H_2O \rightarrow CO_2 + H_2$

Source: Yusup, Phuong Anh, and Zabiri, 2010 and Riaz, Zahedi, and Klemeš, 2013

The kinetics of the chemical reactions involved in the process of catalytic synthesis of methanol is the following (Riaz et al., 2013):

$$r_{CO} = \frac{k_1 f_{CO} f_{CO}^2 (1-\beta_1)}{(1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + K_{H_2} f_{H_2})^3} \quad (1)$$

$$r_{CO_2} = \frac{k_2 f_{CO_2} f_{H_2}^2 (1-\beta_2)}{(1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + K_{H_2} f_{H_2})^4} \quad (2)$$

Where,

$$\beta_1 = \frac{f_M}{K_{f_1} f_{CO} f_{H_2}^2} \quad (3)$$

$$\beta_2 = \frac{f_M f_{H_2O}}{K_{f_2} f_{CO_2} f_{H_2}^3} \quad (4)$$

$$k_1 = 191,2e^{-\left(\frac{41,770}{RT}\right)} \quad (5)$$

$$k_1 = 6,392e^{-\left(\frac{60,920}{RT}\right)} \quad (6)$$

$$K_{CO} = e^{-2,902-29,640\left(\frac{1}{T}-\frac{1}{508,9}\right)} \quad (7)$$

$$K_{H_2} = e^{-1,692+2001\left(\frac{1}{T}-\frac{1}{508,9}\right)} \quad (8)$$

In this proposed mathematical model, r denotes the reaction rate; f, fugacity; T, temperature; and R, the ideal gas constant.

The chemical synthesis processes that use catalysts (such as the production of methanol with copper-based catalysts) are very sensitive to the presence of sulfur and carbon dioxide (Holmgren et al., 2012). These compounds must be removed; otherwise, syngas conversion is restricted, and operating costs increase due to the continuous replacement of the catalyst due to poisoning, aging, or reduction of its active sites. Another issue found in industrial-scale methanol synthesis is the limitation imposed by the thermodynamic equilibrium. Therefore, many efforts are focused on developing technologies that expand methanol production by removing subproducts with selective membranes. However, for this purpose, mathematical and optimization models should be created to compare their efficiency and functionality to traditional methods.

To purify methanol, a distillation tower can be used to remove the greatest possible number of impurities that may affect its quality, value, or simply the subsequent processes which use this product as raw material. This is the case of the production of dimethyl ether (DME), another potential substitute of diesel (Gangadharan et al., 2012; Pontzen et al., 2011; Ravaghi-Ardebili and Manenti, 2015).

Fischer-Tropsch process

This process was developed by German inventors Franz Fischer and Hans Tropsch in the 1920's to produce liquid hydrocarbons (Buragohain et al., 2010b; Damartzis and Zabaniotou, 2011). It is a catalytic technique by which synthesis gas ($CO + H_2$), also known as syngas, is transformed into a mixture of hydrocarbons: olefins, paraffins, waxes, and oxygenated products (synthetic fuels) or naphtha, a precursor in gasoline production (Arsalanfar et al., 2012; Buragohain et al., 2010b; Damartzis and Zabaniotou, 2011). The product obtained from this process greatly depends on the temperature, operating pressure, and the type of catalyst in use (Damartzis and Zabaniotou, 2011), which is generally made of metals in Group VIII such as iron (Fe), cobalt (Co), nickel (Ni), and ruthenium (Ru) (Arsalanfar et al., 2012). Equation (9) illustrates the general chemical reaction that represents this process:

$$(2n+1)\,H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O \quad (9)$$

A conventional catalyst based on cobalt (Co) enables the production of paraffinic diesel oils and, despite being expensive, it presents high activity at low temperatures and a ratio of H_2/CO or stoichiometric number (SN) value of 2, which extends the useful life of the catalyst and prevents deactivation due to sintering or ageing (Buragohain, Mahanta, and Moholkar, 2010a; Kim, Jun, Joo, Han, and Song, 2009). Additionally, a Fe-based catalyst has also been developed to produce hydrocarbons, namely olefinic gasolines extracted from syngas with a substoichiometric H_2/CO ratio, i.e., less than 2 (Buragohain et al., 2010a). Figure 6 presents a diagram of syngas production and exploitation through the Fischer-Tropsch process. Furthermore, it shows some of the conditions and characteristics of this catalytic transformation process of syngas into fuels:

The main Fischer-Tropsch reactions can be divided into five basic steps:

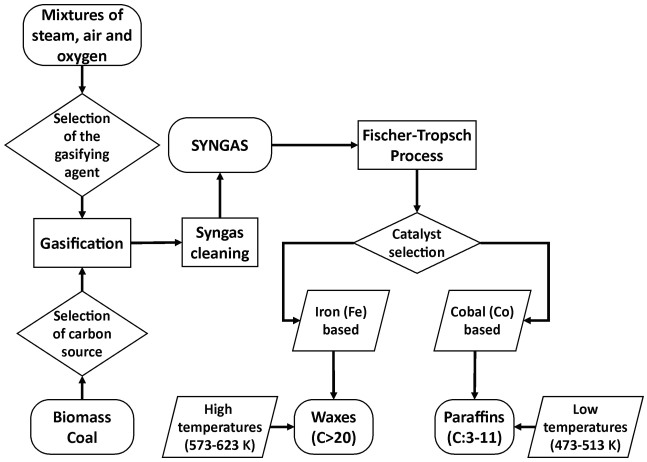

Figure 6. Diagram of syngas production and exploitation by catalytic Fischer-Tropsch.
Source: Authors

1. Adsorption of CO on the surface of the catalyst
2. Start of the polymerization by formation of a methyl radical (by dissociation of CO and hydrogenation)
3. Polymerization by condensation (addition of CO and H_2, and water release)
4. Termination
5. Product desorption

The chemical equations of the reactions in a Fischer-Tropsch process are detailed in Table 7. Reaction 7 represents the transformation of the syngas into the products of interest: fuels with a number of carbon (C) atoms greater than 5.

Table 7. Chemical reactions in the Fischer–Tropsch process

Chemical equation	Reaction
$CO+3H_2 \rightarrow CH_4+H_2O$	(1)
$2CO+4H_2 \rightarrow C_2H_4+2H_2O$	(2)
$2CO+5H_2 \rightarrow C_2H_6+2H_2O$	(3)
$3CO+7H_2 \rightarrow C_3H_8+3H_2O$	(4)
$4CO+9H_2 \rightarrow n-C_4H_{10}+4H_2O$	(5)
$4CO+9H_2 \rightarrow i-C_4H_{10}+4H_2O$	(6)
$6,05CO+12,23H_2 \rightarrow C_{6,05}H_{12,36}(C5^+)+6,05H_2O$	(7)
$CO+H_2O \rightarrow CO_2+H_2$ (Water-gas reaction)	(8)

Source: Authors

Kinetics depend on the selected type of catalyst. For that reason, Table 8 reports the parameters of two power-law kinetics. The first one corresponds to a Fischer-Tropsch (FT) process with a catalyst based on Co and supported by Alumina (Co/Al2O3); the second one is based on Fe.

Moreover, Table 9 summarizes the chemical reactions of a mechanism that involves a Fischer-Tropsch process with a catalyst based on cobalt (Co), iron (Fe), and manganese (Mn).

Table 8. Kinetic model parameters for the Fischer-Tropsch process with Cobalt (Co) and iron (Fe) catalysts

Kinetic model for a cobalt-based (Co) catalyst				
$R_j = A_j \exp\left(\frac{E_j}{T*R_g}\right) P_{CO}^n P_{H_2}^m$				
Reaction	n	m	E_j **[kJ/mol]**	A_j **[mol*$Pa(n+m)/g*s$]**
R. 1	-0,39	1,02	101,15	5,45E+01
R. 2	-0,24	0,15	78,79	1,20E-03
R. 3	-0,26	0,18	59,95	1,45E-03
R. 4	-0,55	0,25	33,73	2,32E-06
R. 5	-0,82	0,35	23,04	2,81E-09
R. 6	-0,76	0,32	17,83	6,57E-10
R. 7	-0,15	1,25	21,25	3,24E-08
R. 8	-1,10	1,26	50,24	5,99E-05
Kinetic model for an iron-based (Fe) catalyst				
$R_j = 0,278k_j \exp\left(\frac{-E_j}{T*R_g}\right) P_{CO}^n P_{H_2}^m$				[mol/Kg*s]
Reaction	n	m	**kJ**	E_j
R. 1	-1,0889	15,662	142.583,8	83 423,9
R. 2	0,7622	0,0728	51,556	65 018
R. 3	-0,5645	13,155	24,717	49 782
R. 4	0,4051	0,6635	0,4632	34 885,5
R. 5	0,4728	1,389	0,00474	27 728,9
R. 6	0,8204	0,5026	0,00832	25 730,1
R. 7	0,5850	0,5982	0,02316	23 564,3
R. 8	0,5742	0,710	410,667	58 826,3

Source: Moazami, Wyszynski, Rahbar, Tsolakis, and Mahmoudi, 2017) and (Rahimpour, Jokar, and Jamshidnejad, 2012.

In turn, Table 10 presents the model and kinetic parameters for this mechanism.

Table 9. Chemical reaction mechanism for a Fischer-Tropsch process with a Co-Fe-Mn catalyst

	Reactions
1	$CO + * \rightleftharpoons CO*$
2	$H_2 + * \rightleftharpoons H_2*$
3	$CO* + H_2* \rightleftharpoons CH_2O* + *$
4	$CH_2O* + H_2* \rightleftharpoons CH_3OH* + *$
5	$CH_3OH* \rightleftharpoons CH_2* + H_2O$

Source: Arsalanfar et al., 2012.

Throughout history, four main types of industrial reactors have been used to produce Fischer-Tropsch reactions (Steynberg, Dry, Davis, and Breman, 2004):

- *Fixed packed-bed tubular reactor*: SASOL (South African Synthetic Oil Ltd) call its reactor of this type Arge, which operates at 220-260 °C and 20-30 bar.
- *Circulating bed reactor*: Named Synthol by SASOL, it operates at 350 °C and 25 bar. It mostly produces olefinic gasoline.

Table 10. Model and kinetic parameters with a catalyst based on cobalt (Co), iron (Fe) and manganese (Mn)

Kinetic model for a catalyzer based on cobalt (Co), iron (Fe) and manganese (Mn)		
$-r_{FT-IX3} = \frac{k_p b_{CO} P_{CO} b_{H_2} P_{H_2}}{(1+b_{CO} P_{CO}+b_{H_2} P_{H_2})^2}$		
Parameter	**Value**	**Units**
k_0	1,6 × 106	mmol/min.g
E_a	825,200	kJ/mol
k(563,15)	0,0356	mmol/min.g
k(57,15)	0,0482	mmol/min.g
k(583,15)	0,0649	mmol/min.g
k(593,15)	0,0865	mmol/min.g
b(CO)	0,2190	bar$^-$ 1
b(H_2)	0,0170	bar$^-$ 1

Source: Arsalanfar et al., 2012.

- *Fluidized bed reactor*: SASOL Advanced Synthol, similar to Synthol in terms of operation but smaller for the same production capacity.
- *Slurry reactor*: The catalyst is suspended in a liquid (often waxes produced by the same reaction) through which synthesis gas is bubbled. Generally, these reactors work at low temperatures to produce a maximum of products with high molecular weight.

Summary of operating conditions of syngas valorization processes

Table 11 summarizes some of the operating considerations and parameters to valorize syngas through thermochemical and catalytic processes and thus obtain thermal energy, electricity, fuels, and high value-added chemical compounds.

Conclusions

The exploitation of second-generation biomass and the integration of phytochemical extraction and thermochemical processes such as gasification at a biorefinery are great alternatives to address the energy crisis and the demand for materials for different industries. This is possible because this kind of facilities are conditioned to abide by sustainability and green chemistry parameters; they are viable as long as they consider the social, environmental, and economic conditions, characteristics, and particularities of their area of influence, so that their implementation truly becomes a driver of industrial development and the production of natural ingredients, highly functional bioproducts, chemicals, fuels, and energy to promote development and well-being.

Few studies in this field consider the phytochemical extraction process from biomass, and they process the entire biomass matrix through thermochemical and biological treatments. Therefore, the proposed biorefinery considers all the value of biomass, due to the extraction of high value-added chemicals

Table 11. Operating conditions of syngas valorization processes

Parameters	**Methanol synthesis**[a]	**Fischer-Tropsch process**[b]
Operating temperature	230-265 °C	240-329 °C
Operating pressure	15-100 bar	20-30 bar
Catalyst	CuO-ZnO $Cu/ZnO/Al_2O_3$, $CuO-ZnO-Al_2O_3$ Ga_2O_3-Pd/Silica $Cu/ZnO/Al_2O_3/ZrO_2$	Co (Cobalt) or Fe (iron) with Al_2O_3.
Equivalence ratio (ϕ) or stoichiometric number (SN)	SN = 2,05	SN = 0,76-1,82
Products	Methanol	Long-chain hydrocarbons, synthetic gasolines, paraffins, etc.
Type of reactor	Multitubular isothermal fixed-bed reactor with a pellet-shaped catalyst operating in gas phase	Slurry reactor with Co catalyst (T = 200°-240 °C) Fluidized bed reactor with Fe catalyst (T = 300°-350 °C)

Source: [a]Manenti, Adani, Rossi, Bozzano, and Pirola, 2016; Riaz, Zahedi, and Klemeš, 2013 and [b]Rauch et al., 2014.

such as phytochemicals, and, simultaneously, by transforming the residual biomass from the extraction into fuel or platform.

Theoretical models for the extraction of phytochemicals and kinetic models for thermochemical processes allow to find the best operating conditions for a biorefinery thorugh computer simulation, thus saving resources in chemical reagents and chemical processes.

Colombia has an agricultural vocation and a remarkably abundant, yet diverse source of biomass. Consequently, the country is currently searching for alternatives that improve profitability in this sector and differentiation in world-wide markets by generating added value. A profitable and sustainable exploitation of biological and genetic resources should be focused on extracting natural high-value ingredients found in this diversity and important sources of waste biomass, such as agro-industrial activities. To support the production and operation costs of the plant, the available biomass must be used rationally, and the greatest possible number of products should be manufactured. However, due to the low content of this type of substances in vegetable matrices, such processing should be conducted at facilities, like biorefineries, that guarantee an efficient extraction and a comprehensive exploitation of this renewable resource.

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A study of the stress field generated by the contact between a sphere and a flat plate for a simplified model of deep-groove ball bearing

Un estudio del campo de tensión generado por el contacto entre una esfera y una placa plana para un modelo simplificado de rodamientos rígidos de bolas

A. O. Köhn[1] and F. de A. Silva[2]

ABSTRACT

Bearings are mechanical elements capable of transferring motion between two or more parts in a machine. When an external load is applied, the rolling elements and their rings tend to initiate a cyclical movement between themselves. Hence, they are linked by a variable type of contact, thus creating high surface stresses. As these elements are subjected to millions of cycles within their lifespan, these cyclical stresses may create cracks and cause failure by rolling contact fatigue (RCF). Due to the importance of this subject, it is vital to study the stress field caused by contact between the rolling parts in a bearing. This paper offers two approaches on the cyclical stresses in a deep-groove ball bearing: an analytical approach, using Hertz's theory for contact stresses; and a numerical simulation, using the Finite Element Method (FEM) with the software *Inventor* and *Nastran In-CAD*. The results of both approaches were compared, and stress behavior was analyzed as the depth of the inner ring was increased. It was concluded that the surface stresses are greatly superior than the strength of the materials used in the bearings, and that the area influenced by these stresses are small when compared to the dimensions of the whole.

Keywords: Hertz contact stress, FEM model, deep-groove ball bearing, surface contact

RESUMEN

Los rodamientos son elementos mecánicos capaces de transferir movimiento entre dos o más partes en una máquina. Cuando se aplica una carga externa, los elementos rodantes y sus anillos tienden a iniciar un movimiento cíclico entre ellos. Por lo tanto, están vinculados por un tipo variable de contacto, creando altas tensiones superficiales. Como estos elementos están sujetos a millones de ciclos en su vida útil, estas tensiones cíclicas pueden crear grietas y causar fallas debido a la fatiga por contacto. Debido a la importancia de este tema, es vital estudiar el campo de tensión causado por el contacto entre las partes rodantes en un rodamiento. Este documento ofrece dos enfoques sobre las tensiones cíclicas en un rodamiento rígido de bolas: un enfoque analítico, utilizando la teoría de Hertz para las tensiones de contacto; y una simulación numérica, utilizando el Método de Elementos Finitos con el software *Inventor* y *Nastran In-CAD*. Los resultados de ambos enfoques se compararon y se analizó el comportamiento de las tensiones a medida que aumentaba la profundidad del anillo interior. Se llegó a la conclusión de que las tensiones superficiales son muy superiores a la resistencia de los materiales utilizados en los rodamientos, y que el área influenciada por estas tensiones es pequeña en comparación con las dimensiones del conjunto.

Palabras clave: estrés por contacto de Hertz, modelo FEM, rodamiento rígido de bolas, contacto superficial

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Introduction

Bearings are mechanical elements used in the naval, aeronautical, automotive and various others branches of the industry. These are crucial elements in the transmission of motion between two parts – for example, a bearing and a shaft. A good bearing performance requires a combination of different parameters acting simultaneously on the element, such as rotation speed, applied loads, lubrication, and geometry of the parts involved in the contact.

Bearings are defined by the type of their rolling elements (balls, needles, rollers, etc), number of rows (single, double, triple), and the type of applied load (radial and/or axial) (Norton,

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2013). The bearing type is chosen based on the conditions and requirements of its application. These machine elements are usually formed by steel rolling elements between two rings (inner and outer), which are retained within a cage.

When an external load initiates rotation, surface contact stresses may cause a subsurface crack, which can grow until it reaches the surface. This endangers the bearing, risking failures such as pitting and spalling, which can compromise the whole machine and cause great financial and human loss.

Due the importance of this matter, many papers seek to understand the mechanism of this problem. However, the study of contact between bearing parts is known to be a complex issue, since the contact area is subjected to stresses as high as 2~5 GPa (Norton, 2013; Rycerz, Olver, and Kadiric, 2017; Morales-Espejel and Gabelli, 2015; Bhattacharyya, Londhe, Arakere, and Subhash, 2017; Li, Hu, Meng, Zhan, and Shen, 2017 Arakere, 2016), as well as several other parameters that have an impact on the situation, such as lubrication, vibration, roughness (Yusof and Ripin, 2014), bearing dimensions (Chen and Wen, 2015), rotation speed, applied loads (Guo, Cao, He, and Yang, 2015), and the curvature of the inner and outer rings (Deng, Hua, Han, and Huang, 2013; Chen and Wen, 2015). Therefore, each parameter must be examined thoroughly, seeking to determine the influence of its behavior on RCF.

Contact between the rolling element and the race creates a triaxial compressive stress field, along with shear stresses in all directions (Bhattacharyya et al., 2017; Arakere, 2016). Many studies showed that shear stresses are responsible for the appearance of cracks (Bhattacharyya et al., 2017; Juvinall and Matshek, 2008; Deng, Hua, Han and Huang, 2014). Studies like Deng, Hua, Han, Wei and Huang (2015) and Deng, Hua, Han and Huang (2013) showed that there will be a peak of stresses around a subsurface material defect, initiating a crack that will spread until it reaches the surface, causing failure of the element.

RCF has a different behavior in each type of bearing, due to the difference in their contact geometry. Morales-Espejel (2014) and Deng et al. (2014) discussed the phenomenon in roller bearings, whereas Li et al. (2017) examined the performance of tapered roller bearings, and Lostado, Martinez, and Donald (2015) studied self-aligning roller bearings. This paper proposes a simplified model for a deep-groove ball bearing.

Neglecting the lubrication effects, the analytical approach for this problem is based on the Hertz equations for contact surfaces (Chen and Wen, 2015). To validate the results, it is crucial to apply the numerical method and a FEM software to obtain the stress field (Lostado et al., 2015). Comparing both approaches, it is possible to achieve a number close to reality.

The contact seen in a deep-groove ball bearing can be simplified using a sphere and flat plane (Norton, 2013). In this paper, the stress field caused by this type of contact was calculated and analyzed. The analysis was performed by using the Hertz equations for contact stress, and these results were compared to the data obtained from the numerical method, using FEM software *Nastran in-CAD* and *Inventor*.

Theoretical analysis

In a deep-groove ball bearing, the rolling elements are in contact with the inner and outer races. When an external load is applied, these balls tend to roll over the race, allowing the transmission of motion between them. This movement consists of 99% rolling and 1% sliding (Norton, 2013).

The contact area is directly related to the geometry and mechanical properties of the materials in contact. Ideally, the contact between a sphere and a flat plate would be represented with a single point with no dimension, generating an infinite stress. However, the applied load causes a small deformation, creating a small contact area with radius a, minimal when compared to the radius of the sphere, causing high compressive stresses. Hence, a high stress field is generated, which may lead to RCF failure of the element. These stresses are much higher than the strength of the materials used in bearings, reaching 2~5 GPa. Figure 1 illustrates the contact area between a sphere and a flat plate in a simplified manner.

Each part of the ball will have touched the race after a rotation is completed. Therefore, this movement creates cyclical stresses described as Hertz stresses (Norton, 2013), thus inducing the formation of pits and spalls and, consequently, complete failure by RCF.

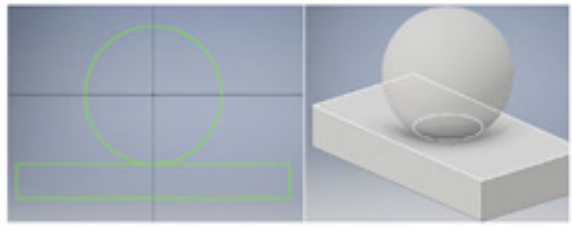

Figure 1. Circular contact zone between a sphere and a flat plate.
Source: Authors

Hertz's stress theory takes into consideration some parameters like surface geometry of the bodies in contact, mechanical properties (Young's Modulus and Poisson ration), and applied loads. Therefore, it is possible to calculate shear and normal stress.

When considering two spheres, Norton (2013) and Juvinall and Matshek (2008) state that the stress between them is dependent on the material and geometrical constants of each sphere. The first is shown in Equation (1), where n is the index that defines each element; and the second is referred to in Equation (2) and involves the curvature of both spheres (R_1 e R_2).

$$m_n = \frac{1 - \upsilon_n{}^2}{E_n} \tag{1}$$

$$b = \left(\frac{1}{2}\right)\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \tag{2}$$

According to Norton (2013) and Juvinall and Matshek (2008), the maximum pressure is seen at the center of the contact region, and P_{mean} is the mean pressure obtained through the division between the applied load F and the contact area of radius a, which is obtained through Equation (5).

$$P_{max} = \frac{3}{2}\frac{F}{\pi a^2} \tag{3}$$

$$P_{mean} = \frac{F}{\pi a^2} \tag{4}$$

$$a = 0,375\sqrt[3]{\frac{m_1 + m_2}{B}F} \tag{5}$$

The applied load F will create a triaxial stress field, in which σ_x, σ_y e σ_z are all compressive and whose maximum is found at the surface. They decrease progressively as the depth is increased (Norton, 2013). The maximum stresses are, at the same time, the main stresses (Juvinall and Matshek 2008).

According to Norton (2013), it is possible to describe the behavior of the shear and the three main normal stresses with Equations (6-8). Plane xy is the one that contains the region of contact between the two surfaces, and z, which represents depth, is the perpendicular axis of this plane.

$$\sigma_x = \sigma_y = \frac{P_{max}}{2}\left[-(1+2\upsilon) + 2(1+\upsilon)\left(\frac{z}{\sqrt{(a^2+z^2)}}\right) + \cdots - \left(\frac{z}{\sqrt{(a^2+z^2)}}\right)^3\right] \tag{6}$$

$$a = 0,375\sqrt[3]{\frac{m_1 + m_2}{B}F}\sigma_z = P_{max}\left[-1 + \frac{z^3}{(a^2+z^2)^{\frac{3}{2}}}\right] \tag{7}$$

$$\tau_{xz} = \tau_{yz} = \frac{P_{max}}{2}\left[\frac{(1-2\upsilon)}{2} + (1-\upsilon)\left(\frac{z}{\sqrt{(a^2+z^2)}}\right) + \cdots - \left(\frac{3}{2}\right)\left(\frac{z}{\sqrt{(a^2+z^2)}}\right)^3\right] \tag{8}$$

Materials and methods

Analytical approach

The calculation was based on a deep-groove ball bearing, from the manufacturer FAG, series 6207. Table 1 shows the dimensions used in Equations (1-9) and Figure 2 illustrates the sectional drawing of a bearing.

The applied load was calculated based on the guidelines for an electric rotor project. The total load applied on the bearing was F = 1 010,6 N. The used model has nine balls, as illustrated in Figure 3. Therefore, it is necessary to divide the total load by the number of rolling elements, thus obtaining 112,3 N. This value was applied to Equations (3-8) to obtain the stress field from the contact surface.

Table 1. Bearing dimensions

Dimensions	Measure
d	35,0 mm
D	72,0 mm
B	17,0 mm
d_1	47,2 mm
D_1	60,7 mm
D_{sphere}	11,0 mm

Source: Authors

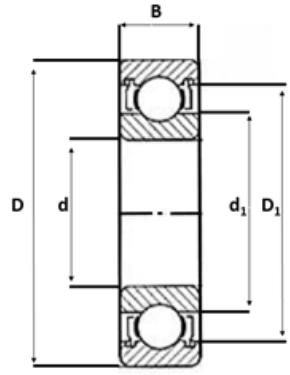

Figure 2. Sectional drawing of bearing.
Source: Authors

Figure 3. Deep-groove ball bearing FAG 6 207.
Source: Authors

As it was mentioned above, the contact region of the ball and race is complex, since it has 4 different curvatures (one radial and one axial for each element). In order to simplify the calculations, it was assumed that one of the bodies is a flat plate. In this case, R_2 tends to infinity, making the Hertz equations easier to calculate. Despite this simplification, the results are still valid and realistic (Norton, 2013).

It was defined that the bearing is made of AISI 52100, the most common steel alloy for this type of operation (Chen and Wen, 2015). Table 2 shows all values used in the calculations.

Using the values from Table 2, the results for B, P_{max}, P_{mean}, as well as stresses σ_x, σ_y, σ_z, τ_{xz} and τ_{yz} were obtained from Equations (3-8). As the maximum normal stresses are observed at the contact plane of the two bodies, z must be zero, or in other words, the depth must equal zero.

Table 2. Values of the parameters used

Sphere Radius	R_1	5,5 mm
Plate Radius	R_2	∞
Young's Modulus (sphere)	E_1	210,0 GPa
Young's Modulus (plate)	E_2	210,0 GPa
Poisson's Ratio (sphere)	υ_1	0,3
Poisson's Ratio (plate)	υ_2	0,3
Applied load in each sphere	F	112,3 N

Source: Authors

Numerical approach

According to Bhattacharyya et al. (2017) and Satyanarayana and Melkote (2004), the contact between a sphere and a flat plate can be simplified to 1/4 of the model due to the contact symmetry, thus maintaining the same characteristics of whole model. Therefore, a computational 1/4 model of the sphere and the flat plate (which represents the inner ring of the bearing) was constructed by means of the FEM software *Inventor* and *Nastran in-CAD,* as seen in Figure 4.

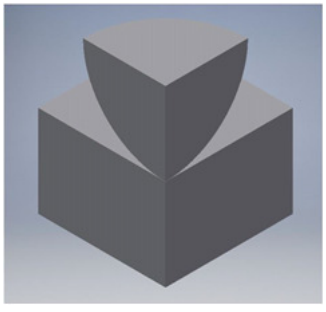

Figure 4. 1/4 model of the sphere and flat plate.
Source: Authors

Constraints

The lower side of the flat plate was fixed with constraints in all directions.

In order to simulate the symmetry of the complete model, symmetry constraints in relation to the axes x and y for the internal faces of the sphere and plate were applied. Therefore, the simplified model behaves exactly as its complete version.

Loads

A compressive load of 112,3 N was applied on the upper side of the sphere. This value represents the load that each sphere receives when a total external load of 1 010,6 N is applied.

Mesh

The mesh was automatically generated by the software. However, it was necessary to refine it at the contact vertex between the sphere and the plate, in order to obtain more precise results.

The final mesh was made with parabolic elements, sized 0,626441 mm, with a tolerance of 1,25288e-05, and it has 6 903 nodes and 4 299 elements.

Surface contacts

The external surface of the sphere is in contact with the upper side of the flat plate. To model according to reality, the option *Sliding/ No Separation* was used for this contact. Hence, it is defined that the parts will not be allowed to separate and will keep attached during the whole operation.

Results and discussion

As it was mentioned before, the contact between the sphere and the race can be simplified to a sphere and flat plate model, and when an external load is applied, a triaxial stress field is created. The shear stresses can cause the appearance of subsurface cracks which may reach the surface, thus causing the failure of the bearing.

With the values mentioned in section 3, it was possible to begin with the analytical and numerical approaches. The results are displayed in Table 3, where a percentage deviation between the results is also presented, in order to show the percentage difference from the stresses obtained by both approaches. All results in Table 3 are located at $z = 0$ and correspond to the maximum values found in the model.

Table 3. Analytical and numerical results

	Analytical (MPa)	Numerical (MPa)	Percentage deviation
σ_x	-1 698,14	-1 667,04 MPa	2%
σ_y	-1 698.14	-1 645,38 MPa	3%
σ_z	-2 122,68	-3 617,99 MPa	70%
τ_{yz}	706,66	682,80 MPa	3%
τ_{xz}	706,66	696,62 MPa	1%

Source: Authors

Analytical results

Applying the parameters previously mentioned in the Equations (3-8), the results for the five maximum stresses were obtained, as indicated in Table 3. The radius of the contact circumference is 0,159 mm, and the contact area between the bodies is 0,0793 mm^2.

As expected, all normal stresses are compressive. The stresses in directions x and y have the same behavior, and they are both in the contact plane of the bodies. The stress in the direction z has maximum values. The shear stresses from planes yz and xz have the same values, and they are both perpendicular to the contact plane of the sphere and the plane. All maximum normal stresses are found in the contact region, that is, where $z = 0$ and the depth is null, as expected. As the depth increases, the stress decreases until it reaches zero.

In order to analyze how these stresses behave as the depth increases, the chart in Figure 5 was created with Equations (6-8). The horizontal axis represents the depth z divided by the constant value of the radius a, and the vertical axis represents the stresses divided by the constant value of P_{max}.

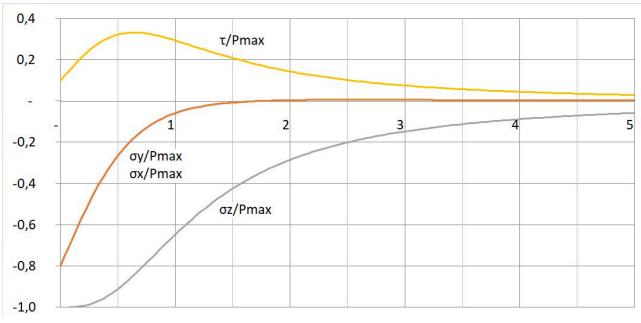

Figure 5. Behavior of the stresses as a function of depth.
Source: Authors

Figure 5 shows that σ_x and σ_y have the same behavior. The maximum stresses are located at $z = 0$ and have values around 0,8 P_{max}. These stresses fall quickly as the depth increases. When the depth reaches approximately 1,5x the value of a, σ_x and σ_y become null.

The maximum stress σ_z has the same value as P_{max}, and its curve declines softer than the stresses in the direction of x and y. Its value tends to zero just when the depth reaches around 5x the value of the radius a.

The maximum shear stress is found under the surface, at approximately $z = 0{,}63a$, and its value is around 0,33 P_{max}.

Consequently, it is possible to conclude that the stresses vary significantly in a small region. For a depth 5x bigger than the circumference radius from the contact area, all stresses are reduced to less than 10% of their maximum value. Thus, it is concluded that the measurement and study of these stresses is a complex subject, since stresses vary drastically within a millimeter region and, moreover, they have considerably high values. The normal stress peak is located at the contact of the bodies, and its values can reach 2 GPa.

Numerical results

Resolving the numerical simulation proposed in the item 3.2, the values of σ_x, σ_y, σ_z, τ_{yz} e τ_{xz} are obtained, as indicated in Table 3.

All maximum normal stresses are located at the vertex of the sphere and plate. Figure 6 shows that the critical point of this simulation for normal stresses is found at the vertex, and, as the depth is increased, this value decreases until it reaches zero. It is also seen that the region affected by the contact stresses is resumed to a small vicinity around the contact vertex.

By comparing the results from the numerical simulation and the analytical data, it can be seen that the results for σ_x, σ_y, τ_{yz} e τ_{xz} are significantly close between the two approaches, and its percentage deviation is around 2%.

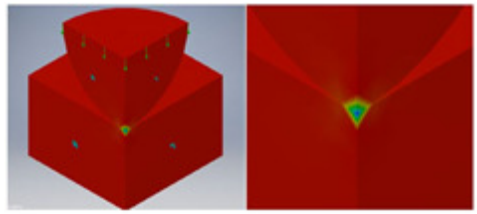

Figure 6. Numerical Result.
Source: Authors

However, the numerical value obtained for σ_z is relatively far from the analytical value.

Four out of five stresses calculated with the FEM software were validated by the analytical calculation. The discrepancy between the values obtained for σ_z can be justified by the inaccuracy from the Hertz equations regarding the thickness of the bodies, that is, the Equations (3-8) do not consider the thickness of the plate. Therefore, the FEM simulation can produce imprecise results compared to the analytical values.

Despite the discrepancy seen in one of the stresses, the theory says that shear stresses are the critical regarding the appearance of cracks that will cause the failure by RCF in the mechanical element. As the percentage deviation seen for this type of stress is around 2%, the FEM model can be validated for this simulation.

Conclusions

The study of the stresses caused by the cyclical contact between a sphere and the race of a deep-groove ball bearing are of high importance, especially regarding the RCF phenomenon. The cyclical contact between the bodies creates a complex high stress field (2~5 GPa), and this process can lead to total failure of the mechanical element.

In this paper, an analytical approach was proposed to study the contact between a sphere and a flat plate, using the Hertz theory for contact surfaces. A numerical method through a FEM model, using the software *Inventor* and *Nastran in-CAD,* was also proposed. The normal stresses obtained by both approaches were always compressive, and their maximum was located at the surface of the bodies. When the depth was increased, these stresses decreased quickly until they reached zero. Therefore, it can be concluded that the region affected by contact stresses is limited to a small vicinity around the contact vertex.

The results of both approaches were satisfactory. In spite of the divergence between the results for the normal stress perpendicular to the contact plane, the shear stresses obtained were similar for both methods, and these types of stresses are the most critical in the appearance of cracks.

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Class entities from the timber house production sector in Brazil

Entidades de clase del sector de producción de casas de madera en Brasil

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ABSTRACT

Corporate representativeness is an important issue for engineering and its industrial sectors, considering that producer associations can defend represent the rights and ambitions of their members. This study aims to investigate timber housing producer participation in generalist organizations, as well as to identify which examples of class entities could be created to consolidate this industry in the Brazilian scenario. A short survey was personally applied to entrepreneurs from the timber house production sector in Brazil. This survey was based in four qualitative queries, whose responses were converted into percentage. The studied producers revealed that the sector does not have an official organization to represent them, forcing them to search for different representation mechanisms from other sectors related to this industry. The lack of corporate and/or labor representation is visible to the point where several interviewed entrepreneurs declared the need to create unions for workers, as well as class associations for producers. Thus, suggestions for a new organization were described to establish a direction for organizing this sector in Brazil.

Keywords: association, union, timber house, sectoral survey, interview

RESUMEN

La representatividad corporativa es un tema importante para la Ingeniería y sus sectores industriales, teniendo en cuenta que la asociación de productores puede defender los derechos y ambiciones de sus miembros. Este estudio tiene como objetivo investigar la participación de los productores de viviendas de madera en organizaciones generalistas, así como identificar qué ejemplos de entidades de clase podrían ser creadas para consolidar esta industria en el escenario brasileño. Se aplicó personalmente una breve encuesta a los empresarios del sector de producción de casas de madera en Brasil. Esta encuesta se basó en dos consultas cualitativas, cuyas respuestas se convirtieron en porcentajes. Los productores estudiados revelaron que el sector no tiene una organización oficial que los represente, lo que tiene obligado en buscar diferentes mecanismos de representación de otros sectores relacionados con esta industria. La falta de representación corporativa y/o laboral es visible al punto en que muchos empresarios entrevistados declararon la necesidad de crear sindicatos para los trabajadores y asociaciones de clase para los productores. Así, se describieron sugerencias de nuevas organizaciones para establecer una dirección en la organización de este sector en Brasil.

Palabras clave: asociación, sindicato, viviendas en madera, encuesta sectorial, entrevista

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Introduction

In order to survive in a competitive environment, an organization must face its challenges head-on, adapt, learn, change, and improve its features and conditions (Abou-Moghli and Al-Abdallah, 2018). However, business associative strategies can avoid this scenario under the mutual growth and institutional development. In Brazil, Jesus (2007) verified that, since the 1850s, when any popular group opted to start an association, people were forced to ask for special authorizations at the police station closest to the place of meeting. Today, this process can be carried out with standard

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guidebooks. For example, if there is public interest in a mobilization, according to Cardoso (2014), at least 10 people are required to create an official association. To this effect, the following stages must be respected: people sensitization, constitution of this future entity, pre-operation through entity structuration, and then, group operationalization and its respective activities.

In general, private organizations with public purposes are those formed by charity institutions, artistic entities, religious groups, professional associations, sectoral representatives, labor unions, and voluntary and community groups (Hudson, 1999).

Private organizations emerge when people from the civil society come together with the aim to consolidate resources and efforts to provide for social needs that cannot be efficiently maintained by the governments (Santos, Camargo, Giuliani, Novaes Netto, and Spers, 2010). Their purpose has been to promote general interests, taking on different legal forms and nomenclatures, and their origins related to the institutional formation and dynamics from each society (Andion, 2005).

Associations may be created due to administrative incompetence and/or lack of public policy to take measures and assign resources to address specific demands (Santos et al., 2010). An industrial association can play the role of a catalyst for change where public intervention does not provide responses to market failure in the development of innovation (Schwartz and Bar-El, 2015). In this way, inflexible laws and public institutions have affected firms' financial gains from corporate entrepreneurship (Vanacker, Zahra, and Holmes, 2017). Such groups are the path to business survival.

Class entities are established as strategic spaces to identify the actions of the economical elites, as well the character and direction of their interests (Loss, 2010). These associations –with distinct ends as scientific, cultural, professional, religious, or even, for charity or recreation– are created to organize, disclose or defend collective material, ideological, political or civil interests (Jesus, 2007). Such initiatives are based on community of origin, usually through a network of common relations (Doucet and Favreau, 1991).

The basic structure of professional or class associations includes the activities related to corporate and employer organizations, professional associations, and labor unions (Salamon and Anheier, 1996). Santos et al. (2010) classified these groups according to their endogenous nature, in the case of activities that benefit their membership –for example, class and employer associations– or exogenous, when they seek a public goods in favor of external people from its social board –such as labor unions.

The regulation of employer and worker classes in Brazil was established by the Decree 19 770, which determined that class associations may be designated as labor unions, federations, and confederations. Their scopes can be local, state-wide and national, respectively (Brazil, 1931). Labor unions emerged in the context of the Industrial Age, in the face of claims to defend workers' rights (Loureiro, 1967). Union actions are not limited to economic and political aspects, but also include the field of formation –in favor of recent knowledge– citizen autonomy, political sense, and politicization, in order overcome the emerging challenges of the capitalist world (Soares and Cabral, 2012).

With a business perspective, Santos et al. (2010) highlighted that associations aim to promote benefits to their members such as providing several services, gaining influence together with local public agencies, uniting representative forces to generate bargaining power with suppliers, and other purposes.

At the end of 1800s, small industrialists from northern Portugal, who felt marginalized in a group dominated by representatives of large textile factories, came together to create the Porto Union of Industrialists to defend national work (Alves, 1996).

Today, most of the existing professions in society rely on associative movements and class entities (Ribeiro, Miranda, and Reis, 2015). Nevertheless, in contrast, different sectors remain unmotivated to join forces in order to obtain representation.

In Brazil, for instance, some niches, such as the timber housing production sector, still do not have direct representation, either for workers or even for construction entrepreneurs. Thus, in parallel with the Brazilian civil construction scenario, some councils, unions and associations focused on this purpose have directed their actions to a group that produces masonry-based buildings, in other words, to the detriment of other construction techniques. In view of this visible exclusion, the creation of representative organizations for all producers and workers from timber housing construction becomes necessary.

This is justified in relation to all the difficulties derived from forest-timber activities, which are very different compared to the obstacles faced by masonry housing producers. Additional information to contribute to the development of small and unrepresented industrial sectors is required. A good effort could be supported by scientific studies.

Industrial studies contribute with information from surveys about production sectors, promoting their knowledge and development. According to the National Institute of Industrial Property (2019), this strategic information on specific sectors is determined to subsidize the elaboration of new regulatory acts to support in the sectoral evaluation of the results from industrial policies, and to allow better utilization of every resource to promote research, development, and technological innovation.

Several studies emerged to supply sectoral issues, as well as to contribute to industry development (Zamora, Delgado, and Sarache, 2014; Pena-Montoya, Osorio-Gomez, Vidal-Holguin, Torres-Lozada, and Marmolejo-Rebellon, 2015; UN/ICC 2015; García-Alcaraz, Adarme-Jaimes, and Blanco-Fernández, 2016;, Vanacker et al., 2017; De Araujo et al., 2018a,b,c; Martins, Steiner, Wilhem, Steiner Neto, and Santos, 2018; Realyvásquez, Maldonado-Macías, García-Alcaraz, 2018; Vishwakarma, Nema, and Sangle, 2018, and others).

The present study aimed to investigate the effective participation of Brazilian timber housing producers in generalist organizations as well as to determine which kinds of class entities could be created to represent and defend the rights and ambitions of this sector. Some hypotheses were listed: most of producers are not part of any organization; the adhesion to general unions of civil construction is still low; and, there is a demand to create an entity to represent timber housing companies and activities.

Experimental development

Given the inexistence of official class entities for Brazilian timber housing producers, any study about this sector becomes limited and arduous, due to the lack of such institutions to share data and information on their respective activities. Therefore, this paper was extracted from a wide research, performed by De Araujo (2017), which aimed to identify and detail the industry, considering the present misinformation in Brazil.

Field of study and considerations

The first stage of this wide research, designed and performed by De Araujo (2017), included the preparation of a list with existing Brazilian timber house producers. After the identification and location of such companies, different information could be obtained, such as the size of the sector and its concentration, that is, the amount of national producers and the state regions with a larger amount of producers. This stage was based on searches on websites from those companies that were prospected for this list, ranging from artisanal to fully industrial productions. This procedure was based on De Araujo et al. (2018a,b,c). After this estimation, the sampling was carried out to characterize the producers in detail and, specifically for the present paper, to verify demands regarding class entities that represent this domestic production sector, since several companies could be prospected and identified in Brazil. Since the studied period, no research has revealed an updated sectoral size, although this totality is still basically active in 2020.

Sampling had limitations in data collection, since face-to-face interviews were carried out with entrepreneurs, either at their company headquarters, at construction events or in timber fields. Due to the large extension of the Brazilian territory, distant regions could imply higher locomotion costs and, consequently, they would be the main limiting factor to the research performance. Thus, a macro-region was designed and considered for data collection, which was based on the largest amount of producers. Such considerations are in the line with the path established by De Araujo (2017) and followed by De Araujo et al. (2018a,b,c).

Survey method and data collection

This study consisted of a survey aiming reveal the real and current situation of the timber house production sector with respect to their representatives and class entities in Brazil. Four questions were formulated for the sampled population to characterize the context in question. The approach and application were in charge of the research manager (first author) and his advisor (last author), with formal support of some researchers from the construction and timber fields (co-authors). A semi-structured questionnaire was created, and its queries are cited and explained in Table 1.

Table 1. Questionnaire queries and response details

Queries	Listed Responses	Response Character
1. Does your company participate in class entities with other companies from timber construction?	a) yes b) no c) not informed	Trichotomic-closed, without any insertions of other responses
2. If affirmative in 1, which kind of class entity does your company participate in?	a) association b) labor union c) cooperative	Hybrid and open, with insertions of extra and simultaneous responses
3. Does your company require a class entity to represent your interests and sectoral demands?	a) yes b) no c) not informed	Trichotomic-closed, without any insertions of other responses
4. If affirmative in 3, exemplify which kind of class entities could be created to supply your demands.		Fully open, with any kind of free responses from interviewees

Source: Authors

Questions 1 and 3 were fully closed and designed to obtain only three possible answers, which could reveal the real panorama of the existence of class entities or their requirement, respectively.

In the second question, only the interviewees who answered 'yes' in the first query could participate, and they were encouraged to answer with the type of group in which their companies are involved. This question is hybrid due to the lack of knowledge of this sector. Finally, the fourth query was created to collect free answers from interviewees regarding the type of organizations they need at this present moment (Table 1). The conclusion of this research was supported by the collected data from timber housing producers, whose qualitative responses were converted into percentage, in order to measure the respective representation and to contribute with assertive discussions for a better sectoral understanding of the prospected scenario.

Statistical method

To validate the obtained results and, consequently, the sampling surveyed in this study, a margin of error was set. For this, the online software for statistical samplings 'Raosoft Sample Size Calculator' from Raosoft (2004) was used to determine the sampling coverage under software prescriptions (a 95% confidence level and a 50% response distribution). A margin of error was obtained and compared with existing literature to certify and validate the research.

Results and Discussion

The performance of this sampling reached 50,95% of the whole sectoral population, as was also declared by De Araujo et al. (2018 a,b,c) with a ± 3,325% margin of error. Also, this statistical tool validated this survey using the definitions by Pinheiro, Castro, Silva, and Nunes (2011), which included two possible levels of reliability to be achieved: acceptable (± 5%) and ideal (± 2,5%).

Table 2. Details of survey and sampling

Results	Amount (Units)	Margin of Error (%)
Estimated amount of overall sectoral population	210	
Sampling amount obtained in the face-to-face interviews	107	6,65

Source: De Araujo (2017) and De Araujo et al. (2018a, b, c).

The verification of a formal presence (by timber house producers) revealed that an expressive parcel of this sampling does not have any participative relationship, even in generalist organizations. Only a small amount of the sampled population did not share data (Figure 1a and Query 1). Thus, the study was quite below the ± 3,325% margin of error.

This situation contrasts with a visible demand for the creation of some kind of representation for this sector, either corporate or from a labor perspective; over the half of the sampled companies feel a lack of representation to cluster all timber house producers in Brazil (Figure 1b and Query 3). This need for a better representation is identified by Lawton, Rajwani, and Minto (2018), since associations are made up of multiple individuals and organizations working toward a shared purpose.

Due to the lack of organizations that are reportedly focused on the timber housing production sector, several companies were motivated to participate in entities from other related activities (Figure 1a).

Thus, associations and labor unions evinced greater adherence among the sampled producers (Figure 2 and Query 2). However, a small portion of the sampled population still officially and strategically declared to be part of technology and research institutes, committees for production and sectoral articulation, and also production cooperatives (Figure 2 and Query 2). This panorama suggests that some companies –in a context lacking representation– have adhered to other distinct sectors to strengthen each other. In view of this problem, associations from different industrial groups have been requested by Brazilian timber house producers to supply this perceived absence, for example, entities from civil construction (mainly focused on masonry), forest production, sawmilling, woodworking, furniture, wood preservation, pulp and paper, general trading, etc. Despite this chronic fact, such producers have been looking for a way to feel more represented because, according to Padilha (2013), class entities have been always created to congregate professionals

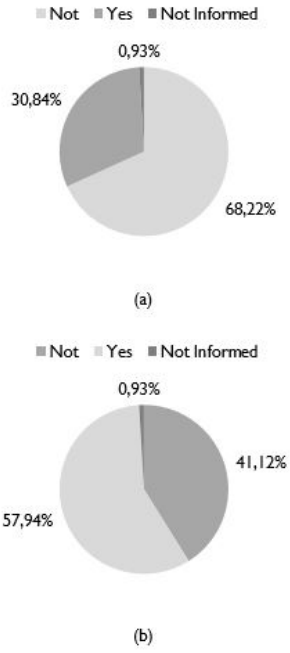

Figure 1. Class entities: (a) formal participation (Query 1) and (b) sectoral demand (Query 3) from sampled producers.
Source: Authors

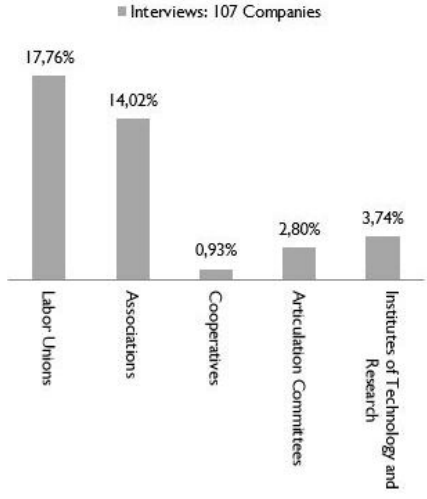

Figure 2. Organizations with participation of sampled companies.
Source: Authors

and to allow actions in defense of specific interests, such as market reserve, fee tables, political lawsuits, etc.

Regarding the demand for greater specific representation, the studied companies reported that associations constitute a basic and immediate need, by virtue of visible claim and pretensions from the timber housing production sector (Figure 3 and Query 4). Thus, the result was more telling when compared to other studies due to the specific focus on class associations, which are meant to represent and defend corporate rights. Due to these noticeable sectoral lacks, the establishment of labor unions was the second essential demand, although its main purpose is to represent workers. This panorama also suggests that some companies are active

in the campaign for workers' rights, which is quite rare in any industrial sector. A small portion of the sampled producers declared the need for the creation of cooperatives, as well as institutes for timber housing research and technology.

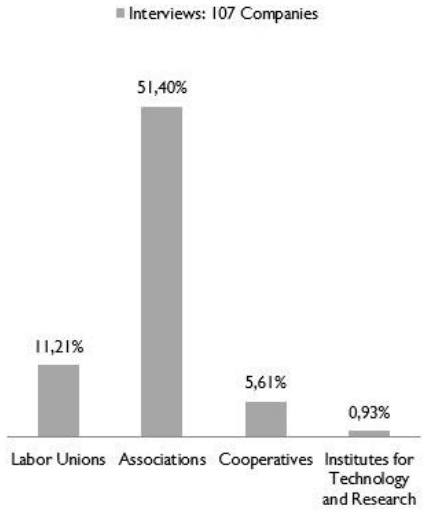

Figure 3. Organization demands from sampled companies.
Source: Authors

Thereupon, the entrepreneurs studied in this sampling pointed out those main demanded organizations (Figure 4 and Query 4). In this figure, the acronyms were used for associations (A), unions (U), cooperatives (C), and for institutes of research and technology (I). Timber housing producer associations were the most prominent in demand, including almost 40% of the interviewees. In a small scale, the studied companies also pointed out other associations and cooperatives focused on timbered construction techniques, wood product producers, woodframe technique builders, etc.

Due to sectoral disarticulation and informality, several producers still declared the need to create labor unions to represent their workers and professionals (Figure 4), denoting this Brazilian production sector' current lack of representation, which was characterized as the second main sectoral demand.

However, regarding the effectiveness of those listed alternatives, articulations will still be necessary, particularly among their future members and their political agendas, as well as public agencies, both in municipal, state and federal contexts.

Most likely, this turning point will be driven by the intensification of construction industrialization –a real phenomenon that is visible in the United States, Sweden, Germany, and Japan, as cited by Koones (2019)– under the need for new cluster formations among suppliers and producers.

In comparison with the current international panorama, several countries focused on the culture of timber utilization already possess class entities to represent their professionals, companies, and groups for science and technology of timber construction. A global perception reveals that several international entities from forest-timber fields are present in the United States, Canada, Germany, Finland, Sweden,

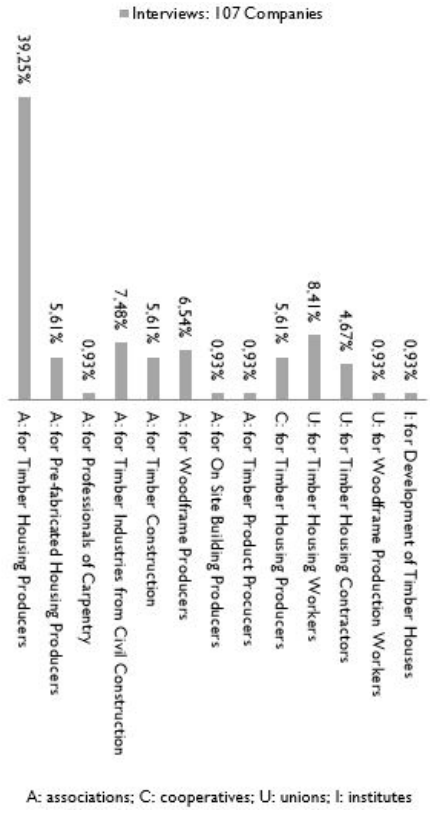

Figure 4. Suggestions about new organizations.
Source: Authors

Norway, Austria, Bosnia, Chile, New Zealand, Australia, etc. However, with respect to these studied producers, some countries concentrate entities for this purpose, for example, Lithuania (Medinių Namų Gamintojų Asociacija, 2007), Estonia (Eesti Puitmajaliit, 2009), and Spain (Asociación de Fabricantes y Constructores de Casas de Madera, 2009).

Conclusions

Formerly, timber housing producers had no official class entities in Brazil, and this situation remains similar in 2020. This fact has forced such companies to seek representation in related sectors, for example, some generalist groups for trade and industry, civil construction (essentially in masonry and steel), or even, in some different associations for other forest and timber activities, which include sylviculture, sawmilling, furniture, wood preservation, etc. This mechanism is rather limited, since most of these entities are not set in the context of timber housing companies, which have domestic presence since the late 1800s.

This lack of representation is noticeable, either from corporative or labor perspectives, that it motivates the sampled entrepreneurs to declare the immediate need to effectively create associations for these producers, as well as labor unions for their workers.

Given the lack of proposals, some new suggestions were listed to create representation and associative channels among producers and workers of the Brazilian timber housing

construction sector. These suggestions aimed to organize and represent the industry in order to defend their needs and interests, together with the national government, with respect to technological improvement, market consolidation, and stimuli for new operations. Associations and cooperatives have been demanded, both for producers and workers, to represent different types of construction techniques, prefabricated houses, timber products, and carpentry.

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Ten-year evolution on credit risk research: a Systematic Literature Review approach and discussion

Diez años de evolución en la investigación de riesgo de crédito: un enfoque y discusión de revisión sistemática de literatura

Fernanda Medeiros Assef[1] and Maria Teresinha Arns Steiner[2]

ABSTRACT

Given its importance in financial risk management, credit risk analysis, since its introduction in 1950, has been a major influence both in academic research and in practical situations. In this work, a systematic literature review is proposed which considers both "Credit Risk" and "Credit risk" as search parameters to answer two main research questions: are machine learning techniques being effectively applied in research about credit risk evaluation? Furthermore, which of these quantitative techniques have been mostly applied over the last ten years of research? Different steps were followed to select the papers for the analysis, as well as the exclusion criteria, in order to verify only papers with Machine Learning approaches. Among the results, it was found that machine learning is being extensively applied in Credit Risk Assessment, where applications of Artificial Intelligence (AI) were mostly found, more specifically Artificial Neural Networks (ANN). After the explanation of each answer, a discussion of the results is presented.

Keywords: credit risk assessment, machine learning, systematic literature review.

RESUMEN

Dada su importancia en la gestión del riesgo financiero, el análisis del riesgo crediticio, desde su introducción en 1950, ha tenido una gran influencia tanto en investigaciones académicas como en situaciones prácticas. En este trabajo se propone una revisión bibliográfica sistemática que considere "Credit Risk" y "Credit risk" como parámetros de búsqueda para responder dos preguntas de investigación principales: ¿se están aplicando efectivamente las técnicas de aprendizaje automático en las investigaciones sobre la evaluación del riesgo de crédito? Incluso, ¿cuáles de estas técnicas cuantitativas se han aplicado mayoritariamente en los últimos diez años de investigación? Se siguieron diferentes pasos para seleccionar los artículos para el análisis, así como los criterios de exclusión para verificar solo los artículos con enfoques de aprendizaje automático. Entre los resultados, se encontró que el aprendizaje automático se está aplicando ampliamente en la Evaluación de Riesgo de Crédito, donde en su mayoría se encontraron aplicaciones de Inteligencia Artificial (AI), más específicamente, de Redes Neuronales Artificiales (ANN). Después de la explicación de cada respuesta, se presenta una discusión sobre los resultados.

Palabras clave: evaluación de riesgo de crédito, aprendizaje automático, revisión sistemática de literatura.

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Introduction

Credit risk analysis is an active research area in financial risk management, and credit scoring is one of the key analytical techniques in credit risk evaluation (Yu, Wang, and Lai, 2009; Steiner, Nievola, Soma, Shimizu, and Steiner Neto, 2007). With the fast development of financial products and services, bank credit departments have collected large amounts of data, which risk analysts use to build appropriate credit risk models to accurately evaluate an applicant's credit risk (Zhang, Gao, and Shi, 2014).

Credit risk evaluation is a data mining research problem, both challenging and important in the field of financial analysis. This assessment is used in predicting whether or not there is a possibility for credit concession. Since its introduction in 1950, it has been extensively applied and, more recently, it has been performed in lending concessions, credit card analysis, and its natural application, credit concession (Luo, Kong, and Nie, 2016).

According to the work of Zhang, Gao, and Shi (2014), there is a wide range of methodologies for solving credit risk classification problems. These methods include mainly logistic regression, probit regression, nearest neighbor analysis, Bayesian networks, Artificial Neural Networks (ANN), decision trees, genetic algorithms (GA), multiple criteria decision making (MCDM), support vector machines (SVM),

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among many others. ANN credit assessment models are highly accurate, but some modeling skills are needed, for example, to design appropriate network topologies. On the other hand, models based on SVM have indicated promising results in credit risk assessment, but they need to solve a convex quadratic programming problem which, computationally, is very expensive in real-world applications.

Looking at the potential benefits that can be achieved through the deployment of research surrounding credit risk, as well as its different methodologies, some questions arise:

Q1. Are machine learning techniques being effectively applied in research about credit risk evaluation?

Q2. Which of these quantitative techniques have been mostly applied over the last ten years of research?

With the objective of seeking answers for these two questions through an extensive search in the available literature, a systematic literature review (SLR) is proposed, as well as a discussion about the obtained results in an attempt to understand the current research landscape and how future works may be steered. The use of SLR does not only contribute to more robust research findings but also enables reproduction and updates of a given review by members of the scientific community. The importance of this work lies in clarifying the current role being played by quantitative methods in Credit Risk Evaluations.

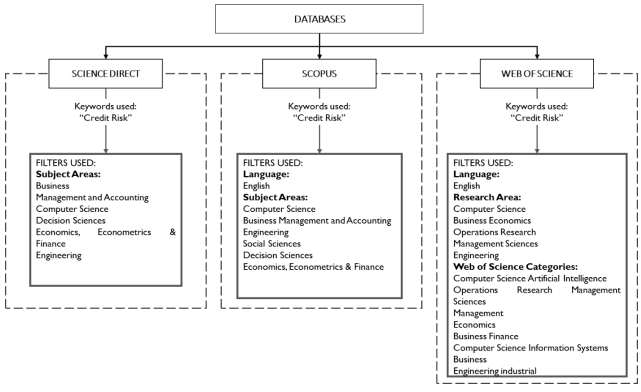

Figure 1. Search filters for each paper database.
Source: Authors

Review Protocol

Having defined the questions, we chose the Web of Science (WoS), Science Direct, and also Scopus databases due not only to their both dynamic and simple interface, but also due to the possibility of obtaining different kinds of analysis from the search.

Systematic literature review method

The search parameters for this research were "Credit risk" and "Credit Risk," both used for this type of research. These keywords were used in the three above-mentioned paper databases.

Initially, 285 documents were found in the Scopus database, 227 in WoS, and 502 in Science Direct. For each database, a few other filters were applied to best select the cut from the total of papers on which we desired to develop our research, these filters and the databases on which they were applied can be found in Figure 1.

At the end of this step, the documents were exported in order to assess their information both in a bibliometric way, as well as through a content analysis, aiming to answer the previous research questions.

Besides the fact that we chose to use three different databases for our paper selection, the originality of our research lies in the types of assessment the authors present in the sections below. We chose to differentiate our bibliometric analysis by presenting the assessment of journals, the number of citations, and a Pareto analysis of each paper's citation. As for the content analysis portion, we present a summary in the form of a table for each paper, as well as a brief analysis.

Credit Risk Assessment Research: the past ten years of research

According to the exclusion criteria shown in Figure 1, 374 documents from the initial amount were approved for the next step of our review: both the bibliometric review and the qualitative content analysis.

As said before, a few premises were considered before starting the content analysis. Since the number of papers found might be too granular, and some papers were not as influential in research as others, we filtered the papers according to their citations (from most to least cited paper). After this step, we considered the proportion that each article had in comparison with the sum of citations from every single one of the collected papers. An example of how this procedure was made is shown below in Table 1.

Table 1. Citation percentage for each paper from the Web of Science

#	Authors	Cited By	%	% Acc
1	Louzis et al. (2011)	987	7,1%	7,1%
2	Cornett et al. (2011)	930	6,7%	13,7%
3	Puri et al. (2011)	591	4,2%	17,9%
4	Firth et al. (2009)	403	2,9%	20,8%
5	Yeh and Lien (2009)	390	2,8%	23,6%
6	Lessmann et al. (2015)	387	2,8%	26,4%
7	Wang et al. (2011)	335	2,4%	28,8%
8	Lee et al. (2015)	303	2,2%	31,0%
9	Khandani et al. (2010)	288	2,1%	33,0%
10	Bellotti and Crook (2009).	287	2,1%	35,1%
...	...	...	...	...

Source: Authors

After doing so, a Pareto analysis was performed in order to find how many papers were responsible for at least 80% of the overall citation found in the search. We chose this amount according to Pareto's Principle, or the 80/20 rule; we brought this management principle to our bibliometric analysis. By

observing the citation amount for each database, we were able to find that 27 papers happened to be responsible for 80% of the sum of citations, which represented 20% of the total of papers in the WoS database –thus confirming the possibility of using the above-mentioned rule.

The same procedure was applied for Scopus (38 papers were selected) and Science Direct (112 papers). Adding WoS 27 papers, Scopus' 38 and Science Direct 112, the 177 selected documents were put together, and the duplicated ones were excluded in order to present a clean-cut from all selected papers. After that, the next step for the proposed review was to apply several exclusion criteria. First, the papers which were not found were excluded; secondly, papers from conferences; after that, the ones without credit risk applications; then, papers before 2009 (they were excluded from the content analysis); and finally, the ones that had theoretical explanations (i.e., papers that did not apply data mining techniques, surveys, state of the art reviews, and theoretical frameworks).

The journals considered for this analysis can be found in Table 2, and their h-index was collected to illustrate their impact. Analyzing this table, we are able to observe that 12 out of 31 journals have an h-index over 100, and the average of the presented journals was around 90.

Table 2. The journals considered for the analyses

Journal	Count	H-Index
European Journal of Operational Research	12	211
Journal of Financial Economics	3	206
Research Policy	1	191
Information Sciences	2	154
Expert Systems with Applications	37	145
Journal of Business Research	1	144
Journal of Banking and Finance	9	126
Computers and Operations Research	1	124
Decision Support Systems	2	115
IEEE Transactions on Systems, Man and Cybernetics: Systems	1	111
Journal of Monetary Economics	1	107
Neurocomputing	1	100
Applied Soft Computing	6	97
Journal of the Operational Research Society	2	87
Computational Statistics and Data Analysis	1	85
Automation in Construction	1	83
Knowledge-Based Systems	3	82
Management Decision	1	77
International Journal of Forecasting	3	74
Journal of Financial Intermediation	3	63
Journal of Empirical Finance	1	63
International Journal of Neural Systems	1	50
Journal of Intelligent Information Systems	1	47
Journal of Applied Statistics	1	45
International Review of Financial Analysis	1	38
Review of Quantitative Finance and Accounting	1	36
Procedia Computer Science	1	34
International Journal of Finance and Economics	1	33
Journal of Financial Stability	1	32
Review of Development Finance	1	9
Intelligent Systems in Accounting, Finance, and Management	1	5

Continued on next column

Source: Authors

Another analysis we were able to obtain concerns the amount of citations each journal received considering the papers selected, as seen in Table 3.

Table 3. Journals and citations amounts

Journal	H-Index	Citation
Expert Systems with Applications	162	4 653
Journal of Banking & Finance	135	2 442
European Journal of Operational Research	226	1 833
Journal of Financial Economics	223	1 646
Applied Soft Computing	110	509
Journal of Financial Intermediation	67	447
International Journal of Forecasting	79	406
Information Sciences	154	389
Decision Support Systems	127	347
Research Policy	206	303
International Review of Financial Analysis	43	255
Journal of Financial Stability	38	237
Knowledge-Based Systems	94	234
Journal of Empirical Finance	66	168
International Journal of Finance & Economics	36	101
Computers & Operations Research	133	95

Continued on next column

Journal	H-Index	Citation
Review of Development Finance	13	95
Journal of the Operational Research Society	94	95
Neurocomputing	110	93
Journal of Monetary Economics	112	85
International Journal of Neural Systems	55	75
Journal of Business Research	158	71
Computational Statistics & Data Analysis	93	63
Procedia Computer Science	47	57
Journal of Intelligent Information Systems	49	55
Automation in Construction	95	49
Journal of Applied Statistics	48	45
Review of Quantitative Finance and Accounting	36	39
IEEE Transactions on Systems, Man and Cybernetics: Systems	111	37
Management Decision	82	32
Intelligent Systems in Accounting, Finance, and Management	5	9

Source: Authors

From Table 3, we were able to assume that journals with a higher h-index were not always cited more than the others. The seven first journals presented in this table represent 80% of the overall citation, being *Expert Systems with Applications, Journal of Banking & Finance, European Journal of Operational Research, Journal of Financial Economics, Applied Soft Computing, Journal of Financial Intermediation,* and the *International Journal of Forecasting*. After analyzing the information surrounding each paper, their content was reviewed, and the Table 4 below was built in order to summarize their information in chronological order. The best performance technique (where possible) is indicated in boldface.

Table 4. Summary of analyzed papers

#	Authors	Cited By	Techniques
1	Antonakis and Sfakianakis, 2009	33	NBR; LDA; LR; kNN; **CT**; **ANN**
3	Bose and Chen, 2009	109	Not Applied
4	Chen, Ma, and Ma, 2009	104	CART; **MARS**; **SVM**
5	Firth et al., 2009	326	Descriptive Statistics
6	Jiménez, Salas and Saurina, 2009	108	Descriptive Statistics
7	Khashman, 2009	63	**SHNN**; DHNN
8	Koopman et al., 2009	139	Proposed technique
9	Lessmann and Vob, 2009	63	RBF SVM; SVM; **LR**; CART
10	Lin, 2009	82	LR; **LLR**; **ANN**
11	Marinakis et al., 2009	83	**ACO**; **PSO**; TS; AG
12	Tsai et al., 2009	52	DA; LR; ANN; **DEA-DA**
13	Xu, Zhou, and Wang, 2009	82	SVM; **HARA**; HubAvgRA; ATkRA
14	Yeh and Lien, 2009	197	KNN; LR; DA; NB; **ANN**; CT
15	Yu, Wang, and Lai, 2009	187	**Fuzzy-GDM**; GDM; SVMR; RBF NN; BPNN; LR;LinR
16	Brown and Zehnder, 2010	73	Descriptive Statistics
17	Cardone-Riportella, Samaniego-Medina, and Trujillo-Ponce, 2010	120	UVA; MVA
18	Dong, Lai, and Yen, 2010	33	LRF; **LRR**
19	Khandani, Kim and Lo, 2010	145	**CART**
20	Khashman, 2010	159	Three architectures of ANN with nine learning methods
21	Malik and Thomas, 2010	53	CPH
22	Marinaki, Marinakis, and Zopounidis, 2010	69	**HBMO**; ACO; PSO; GA; TS
23	Paleologo, Elisseeff, and Antonini, 2010	122	SVMLin; ANN; **DT**; SVM-RBF; AdaBoost
24	Psillaki, Tsolas, and Margaritis, 2010	147	DEA; **LR**
25	Tsai and Chen, 2010	98	DT; **ANN**; NBC; **LR**; K-Means; EM
26	Twala, 2010	122	LD; KNN; NBC; ANN; **DT** (combined with whether Feature Selection, Boosting or Both)
27	Zhou, Lai, and Yu, 2010	125	LDA; DLDA; QDA; DQDA; LR; PR; ID3; CART; BPNN; ProbNN; BC; KNN; AdaBoost; **LSSVMRBF**; **LSSVMLin**; 1nSVMRBF

Continued on next column

#	Authors	Cited By	Techniques
28	Andrés et al., 2011	104	MARS; **Fuzzy C-Means**; ANN; DA
29	Cerqueiro, Degryse, and Ongena, 2011	86	Descriptive Statistics
30	Cornett et al., 2011	698	Descriptive Statistics; Regression Models (Not Specified)
31	Finlay, 2011	106	LR; LDA; CART; ANN; KNN; **ET Boost**
32	Hájek, 2011	85	ANN; RBF NN; **ProbNN**; CCNN; GMDH; SVM; MDA; LR; K-Means; CT
33	Huysmans et al., 2011	152	DT; **Dtab**
34	Khashman, 2011	65	12 Different architectures of EmBP and ANN (six of each)
35	Li et al., 2011	80	MDA; Logit Regression; CBR + kNN; CBR + DT; SPNIC-CBR; **SVM**
36	Louzis, Vouldis, and Metaxas, 2011	618	Descriptive Statistics; **GMM**
37	Magri and Pico, 2011	89	Descriptive Statistics
38	Peng et al., 2011	110	MCDM (TOPSIS, PROMETHEE, VIKOR); **NB**; LR; KNN; SVM; RBF NN;
39	Puri, Rocholl, and Steffen, 2011	500	Descriptive Statistics; Bivariate Tests
40	Tseng et al., 2011	37	**ESVM**; LR
41	Wang et al., 2011	210	**LRA**; **DT**; ANN; SVM; Bagging
42	Yap, Ong, Husain, 2011	121	Credit Scorecard Model; **LR**; DT
43	Zambaldi et al., 2011	54	PR
44	Zhou *et al.* 2011	25	SVM; **KASNP**
45	Derelioğlu and Gurgen 2011	42	**RFE-SVM**; CRED; DT; **MLP**; k-NN
	Wang and Ma, 2012	109	**RSB-SVM**
46	Koyuncugil and Ozgulbas, 2012	133	**CHAID**
47	Kwak *et al.* 2012	39	**MCLP**
48	Akkoç, 2012	127	LDA; LRA; ANN; **ANFIS**
48	Bellotti and Crook, 2012	87	**OLS**; DT
50	Bijak and Thomas, 2012	41	**CART**; **CHAID**; LOTUS; LR
51	Capotorti and Barbanera, 2012	56	Hybrid proposed by the authors

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#	Authors	Cited By	Techniques
52	Chang and Yeh, 2012	43	**AINE**; AIRS; SAIS
53	Chi and Hsu, 2012	61	HGADSM
54	Crone and Finlay, 2012	90	LR; LDA; CART; ANN
55	Hens and Tiwari, 2012	51	SVM; SVM + GA; BPNN; **GP**
56	Loterman et al., 2012	94	OLS; B-OLSBR; BC-OLS; RiR; RoR; RT; MARS; **LSSVM**; **ANN**; LR+OLS; LR+B-OLS; LR+BR; LR+BC-LS; LR+RiR; LR+RoR; LR+RT; LR+MARS; LR+LSSVM; LR+ANN; OLS+RT; OLS+MARS; OLS+LSSVM; OLS+ANN; OLS + MARS; OLS + LSSVM; OLS + ANN
57	Marqués, García, and Sánchez, 2012	58	ANN; LR; SVM; AdaBoost; **Bagging**; RSM; **RF**
58	Marqués, García and Sánchez, 2012b	56	ANN; NBC; LR; RBF NN; **SVM**; C4.5
59	Menkhoff, Neuberger and Rungruxsirivorn, 2012	87	Descriptive Statistics
60	Oreski, Oreski, and Oreski, 2012	117	**GANN**; FSNN; NNGM
61	Sánchez-Lasheras et al., 2012	47	**SOM**; **MARS**; BPNN
62	Tong, Mues and Thomas, 2012	67	MCM; CPH; **LR**
63	Van et al., 2012	80	LR
64	Vukovic et al., 2012	49	**CBR**; KNN; **GA**; **PF**
65	Wang et al., 2012	108	LRA; LDA; MLP; RBF NN; **RS-Bagging DT**; Bagging-RS DT
66	Wang et al., 2012	48	RSFS; ANN; DT; LR
67	García *et al., 2012*	33	Data Filtering
68	Blanco et al., 2013	103	**MLP**; LDA; QDA; LR
68	Chen et al., 2013	59	SOM; FSOM; TSOM
70	Cotugno, Monferrà, and Sampagnaro, 2013	83	Descriptive Statistics; MRA
71	Harris, 2013	35	Seven Models of SVM
72	Kruppa et al., 2013	61	LR; KNN; BNN; **RF**
73	Miguéis, Benoit, and Van Den Poel, 2013	19	BBQR
74	Tinoco and Wilson, 2013	159	**LR**

Continued on next column

#	Authors	Cited By	Techniques
75	Zhu et al., 2013	26	TOPSIS; **C-TOPSIS**; LDA; QDA; DT; LR; kNN; SVM; LSSVM
76	Kou et al., 2014	389	**MCDM**
77	Bekhet and Eletter, 2014	47	**LR**; RBF NN
78	Bubb and Kaufman, 2014	71	Not Applied
79	Ferreira et al., 2014	26	MCDM; **MACBETH**
80	García, Marqués, and Sánchez, 2014	38	MLP; SVM; 1-NN; C4.5
81	Jankowitsch, Nagler, and Subrahmanyam, 2014	89	Descriptive Statistics
82	Oreski and Oreski, 2014	147	HGANN
83	Zhang, Gao, and Shi, 2014	36	MCOC; SVM; Fuzzy-SVM; **KFP-MCOC**
84	Zhong et al., 2014	76	ANN; ELM; I-ELM; **SVM**
85	Wu et al., 2014	37	**LR**; DT; ANN
86	Danenas and Garsva, 2015	46	**CSVM**; SVM; LSVM
87	Florez-Lopez and Ramon-Jeronimo, 2015	21	LDA; LR; kNN; **SVM**; ANN; CHAID; C4.5; CART; **Gradient Boosting**; RF; SVDF; WVDF; CADF
88	Ghosh, 2015	95	GMM
89	Harris, 2015	103	**CSVM**; SVM; LinR; LR; DT; ANN
90	Iturriaga and Sanz, 2015	75	DA; LR; RF; **ANN**; **SVM**; SOM
91	Laeven, Levine, and Michalopoulos, 2015	175	Proposed technique but not applied
92	Lee, Sameen, and Cowling, 2015	144	Descriptive Statistics
93	Lessmann et al., 2015	173	Not Applied
94	Zhao et al., 2015	55	MLP
95	Zhou et al., 2015	37	FVIF; WMBGA
96	Sousa et al., 2016	48	Framework
97	Guo et al., 2016	161	P2P
98	Cleofas-Sánchez et al., 2016	28	LR; ANN; SVM; **Hybrid**
99	Lahmiri, 2016	9	Feature Selection; SVM; ANN; Bayes NN
100	Beck et al., 2016	112	Not Applied
101	Abellán and Castellano, 2017	20	**LR**; **MLP**; SVM; **C4.5**; **CDT** - combined with AdaBoost, **Bagging**, Random Subspace, DECORATE, Rotation Forest

Continued on next column

Legend: 1nLSSVMRBF (1-Norm Support Vector Machines With Radial Basis Functions Kernel); 1-NN (1 Nearest Neighbor); ACO (Ant Colony Optimization); AINE (Artificial Imune Network); AIRS (Artificial Immune System); ANFIS (Adaptive Neuro Fuzzy System); ANN (Artificial Neural Networks); ATkRA (At K Ranking Applicants Algorithm); AV (Account Variables); BBQR (Bayesian Binary Quantile Regression); BC-OLS (Box–Cox Transformation Ordinary Least Squares Estimation); bNN (Bagged k-Nearest Neighbors); B-OLS (Beta Transformation Ordinary Least Squares Estimation); BPN (Back Propagation Network); BPNN (Back Propagation Neural Networks); BR (Beta Regression); C4.5 (C4.5 Decision Tree); CADF (Correlated-Adjusted Decision Forests); CART (Classification and Regression Trees); CBR (Case-Based Reasoning); CCNN (Cascade Correlations Neural Networks); CDT (Credal Decision Tree); CHAID (Chi-square automatic interaction detection); MCOC (Multi-Criteria Optimization Classifier); CPH (Cox Proportional Hazards); CRM (Cox Regression Model); CT (Classification Trees); C-TOPSIS (Classification Technique for Order Preference by Similarity to Ideal Solution); CRED (Continuous/Discrete Rule Extractor via Decision Tree Induction); DA (Discriminant Analysis); DA (Discriminant Analysis); DEA (Data Envelopment Analysis); DHNN (Double Hidden Layer Neural Networks); DLDA (Diagonal Linear Discriminant Analysis); DQDA (Diagonal Quadratic Discriminant Analysis); DT (Decision Trees); Dtab (Decision Table); ELM (Extreme Learning Machine); EM (Expectation Maximization); EmBP (Emotional Back Propagation); ESVM (Enforced Support Vector Machines Based Model); ET Boost (Error Trimmed Boosting); FSNN (Feature Selection Neural Networks); FSOM (Feature Self-Organizing Maps); FVIF (Filter Method and Variance Inflation Method); GA (Genetic Algorithm); GANN (Genetic Algorithm Neural Networks); GDM (Group Decision Making); GMDH (Group Method of Data Handling); GMM (Generalized Method of Moments); GP (Genetic Programming); HARA (Hub Authority Ranking Applicants); HBMO (Honey Bee Mating Optimization); HGADSM (Hibrid Genetic Algorithm into Dual Scoring Model); HGANN (Hybrid Genetic Algorithm Neural Network); HubAvgRA (Hub-Avb Ranking Applicants Algorithm); ID3 (Decision Trees with different Tree Construction Algorithms); I-ELM (Incremental Extreme Learning Machine); IOM (Instance-Based Model; KASNP (a kernel-based learning method called kernel affine subspace nearest point); KFP-MCOC (Kernel, Fuzzyfication and Penalty Factors Multi-Criteria Optimization Classifier); KNN (k-Nearest Neighbors); LD (Logistic Discrimination); LDA (Linear Discriminant Analysis); LinR (Linear Regression); LLR (Logarithm Logistic Regression); LR (Logistic Regression); LRA (Logistic Regression Analysis); LRF (Logistic Regression with Fixed Coefficients); LRR (Logistic Regression with Random Coefficients); LSSVMLin (Least Square Support Vector Machines with Linear Kernel); LSSVMRBF (Least Square Support Vector Machines with Radial Basis Functions Kernel); MACBETH (Measuring Attractiveness is applied by a Categorical Based Evaluation Technique); MARS (Multivariate Adaptive Regression Splines); MCDM (Multiple Criteria Decision Making); MCM (Mixture Cure Model); MLP (Multilayer Perceptron); MV (Macroeconomic Variables); MCLP (Multiple Criteria Linear Programming); MVA (Multivariate Analysis); NB (Naive Bayesian); NBC (Naive Bayes Classifier); NNGM (Generic Model for Parameters Optimization of the Artificial Neural Network); OLS (Ordinary Least Squares Estimation); P2P (Peer-to-Peer); PF (Preference Functions); PR (Probit Regression); ProbNN (Probabilistic Neural Networks); PROMETHEE (Preference Ranking Organization Method for Enrichment of Evaluations); PSO (Particle Swarm Optimization); QDA (Quadratic Discriminant Analysis); RBF NN (Radial Basis Functions Neural Networks); RBM (Basic Rating-Based Model); RBM+ (Refined Rating-Based Model); RiR (Ridge Regression); RoR (Robust Regression); RSB-SVM (Random Subspace Support Vector Machine); RSFS (Random Subset Feature Selection); RFE-SVM (recursive feature extraction with support vector machines); RSM (Random Subspace Method); RT (Regression Tree); SAIS (Simple Artificial Imune System); SHNN (Single Hidden Layer Neural Networks); SME (Small and Medium Enterprises); SOM (Self-Organizing Maps); SPINIC-CBR (Similarities to Positive and Negative Ideal Cases - Case-Based Reasoning); SVDF (Simple Majority Vote); SVM (Support Vector Machines); SVMLin (Support Vector Machines With Linear Kernel); SVMR (Support Vector Machines Regression); SVMRBF (Support Vector Machines With Radial Basis Functions Kernel); TOPSIS (Technique for Order Preference by Similarity to Ideal Solution); TS (Tabu Search); TSOM (Trajectory Self-Organizing Maps); UVA (Univariate Analysis); VIKOR (*VlseKriterijumska Optimizacija I Kompromisno Resenje* [Multi-criteria Optimization and Compromise Solution]); WMBGA (Wrapper Method Based on Genetic Algorithm); WVFD (Weighted Majority Vote).

Source: Authors

The first noticeable thing after analyzing the papers is that with all the filters applied, not many papers from 2017 until today were shown. In order to include these documents, the same research agenda was applied to the last two years

from 2017 until now. After selecting from the bases and filtering with the same 80% citation criteria and excluding theoretical and repeated papers, the remaining papers for analysis amounted to 15, as shown below in Table 5.

Table 5. Summary of analyzed papers (2017-2019)

#	Author	Cited By	Methods
1	Xia et al. 2017	149	TPE; RS; GS; MS; **XGBoost**; AdaBoost; ANN; DT; Bagging; DT; LR; RF; SVM; GBDT
2	Barboza, Kimura, and Altman, 2017	145	SVMLin; SVM RBF; **Boosting**; Bagging; **RF**; ANN; LR; MDA
3	Sun *et al*. 2018	75	**Bagging**; DTE-SBD; **DT**; SMOTE; DSR
4	Luo, Wu, and Wu D., 2017	60	SVM; **DBN**; MLR; MLP
5	Li *et al*. 2017	48	**SSVM**
6	Xia, Liu, and Liu, 2017	48	LR; RF; CSLR-T; CSRF-T; CSLR-SMOTE; CSRF-SMOTE; **CSXGBoost**
7	Bequé and Lessmann, 2017	45	ELM; ANN; KNN; **SVM-Lin**; SVM RBF; CART; J48; **LR-R**
8	Lanzarini *et al*. 2017	44	C4.5; **LVQ+PSO**
9	Xia *et al*. 2018	37	LR; GPC; SVM; DT; SVM Bagging; GPC Bagging; **RF**; **XGBoost**; **MV**
10	Kvamme *et al*. 2018	30	**CNN**
11	Tavana *et al*. 2018	30	**ANN**; BNN
12	Maldonado *et al*. 2017	25	**Logit Regression**; FS; RFE-SVM; HOSVM; SVM
13	Dirick et al., 2017	21	AFT; **CPH**
14	Moradi and Rafiei, 2019	12	ANFIS
15	Khemakhem and Boujelbene, 2018	9	SMOTE; ANN; DT

Legend: TPE (Tree-Structured Parzen Estimator); RS (Random Search); GS (Grid Search); MS (Manual Search); XGBoost (Extreme Gradient Boosting); GBDT (Gradient Boosting Decision Tree); ANN (Artificial Neural Networks); DT (Decision Trees); LR (Logistic Regression); RF (Random FoSynthetic Minority Over-Sampling Technique);; SVM (Support Vector Machines); SVMLin (Linear Support Vector Machines); SVM RBF (Radial Basis Functions Support Vector Machines); MDA (Multivariate Discriminant Analysis); SMOTE (Synthetic Minority Over-Sampling Technique); DSR (Differentiated Sampling Rates); DTE-SBD (Decision Tree Ensemble based on SMOTE, Bagging and DSR); DBN (Deep-Belief Network); MLR (Multinomial Logistic Regression); SSVM (Semi-Supervised Support Vector Machines); CSLR-T (Thresholding Logistic Regression); CSRF-T (Thresholding Random Forests); CSLR-SMOTE (Logistic Regression Balanced with Synthetic Minority Over-Sampling Technique); CSRF-SMOTE (Random Forests Balanced with Synthetic Minority Over-Sampling Technique); CSXGBoost (Cost-Sensitive Extension of Xgboost); ELM (Extreme Learning Machines); KNN (K-Nearest Neighbours); CART (Classification and Regression Trees); LR-R (Regularized Logistic Regression); C4.5 (C4.5 Decision Trees); LVQ PSO (Learning Vector Quantization Particle Swarm Optimization; GPC (Gaussian Process Classifier); MV (Majority Voting); BNN (Bayesian Neural Networks); FS (Fisher Score); RFE-SVM (Recursive Feature Elimination Support Vector Machines); HOSVM (Holdout Support Vector Machines); AFT (Accelerated Failure Time); CPH (Cox Proportional Hazards); ANFIS (Adaptive Network-based Fuzzy Inference System); SMOTE (Synthetic Minority Oversampling Technique)

Source: Authors

As for the analysis of the journals from the past two years, it can be found in Table 6.

Table 6. Journals and citations amounts

Journal	H-Index	Citation
Expert Systems with Applications	162	468
Information Sciences	154	75
Engineering Applications of Artificial Intelligence	86	60
Electronic Commerce Research and Applications	62	48
Neurocomputing	110	30
Decision Support Systems	127	30
Journal of the Operational Research Society	94	25
Kybernetes	33	21

Source: Authors

Research without comparison between results

Among the analyzed papers, 30 documents did not compare the applied techniques nor the author-proposed ones, not being able to verify their performance. Thus, they will be the first papers to be assessed in this first part of the content analysis.

There were initially the papers which used only descriptive statistics as their means to evaluate credit risk, either to evaluate the broader effects of the US financial crisis on global lending to retail customers (Puri, Rocholl, and Steffen, 2011), or even to examine how the Chinese state-owned banks allocate loans to private firms (Firth, Lin, Liu, and Wong, 2009). Among the analyzed papers, authors were found whose main concern was to address the hardship that SMEs (Small and Medium Enterprises) may find in order to access financial aid or credit for investments (Lee, Sameen, and Cowling, 2015).

With more of a qualitative approach, Guo, Zhou, Luo, Liu, and Xiong (2016) used an instance-based model to assess a loan's credit risk by formulating P2P lending into portfolio optimization with boundary constraints. The authors then described the similarity between two loans by using default likelihood distance. Also, Sousa, Gama, and Brandão (2016) developed an approach to deal with changing environment in credit risk modeling by establishing a framework for this assessment. An application to a real-world financial dataset of credit cards from a financial institution in Brazil illustrates our methodology, which is able to consistently outperform the static modeling schema.

There were also authors who performed their research about the effects of organizational distance on the use of collateral for business loans by Spanish banks on the basis of the recent lender-based theory of collateral (Jiménez, Salas, and Saurina, 2009). Others considered the recovery rates of defaulted bonds in the US corporate bond market, based on a complete set of traded prices and volumes (Jankowitsch, Nagler, and Subrahmanyam, 2014), other researchers concerned with assessing how much mortgage interest rates in Italy are priced on credit risk as proxied by the probability of household mortgage delinquency, estimated by using the EU-Silc database (Magri and Pico, 2011).

There were other papers in which, due to opaque information and weak enforcement in emerging loan markets from 2012, the authors assessed the need for high collaterals, whereas borrowers lack adequate assets to pledge. For this, they found for a representative sample from Northeast Thailand where indeed most loans do not include any tangible assets as collateral (Menkhoff, Neuberger, and Rungruxsirivorn, 2012). We also found a paper that investigates the determinining factors of dispersion in interest rates on loans granted by banks to small and medium sized enterprises. The authors associated this dispersion with the loan officers' use of 'discretion' in loan rate setting process, and found that it was very important if: (i) loans were small and unsecured; (ii) firms were small and opaque; (iii) the firm operated in a large and highly concentrated banking market; and (iv) the firm was distantly located from the lender (Cerqueiro, Degryse, and Ongena, 2011). In the work developed by Cotugno, Monferrà, and Sampagnaro (2013), the authors examined the firms' credit availability during the 2007-2009 financial crisis using a dataset of 5,331 bank-firm relationships provided by borrower credit folders from three Italian banks. It aimed to test whether a strong lender-borrower relationship can produce less credit rationing for borrowing firms, even during a credit crunch period. And the final paper, which used only descriptive statistics in its analysis, provides the first systematic empirical analysis of how asymmetric information and competition in the credit market affect voluntary information sharing between lenders. Their study surrounded an experimental credit market in which information sharing can help lenders to distinguish good borrowers from bad ones (Brown and Zehnder, 2010).

There were also papers which actually developed either machine learning or statistic-based techniques but did not compare the result against what was tested. For instance, Cornett, McNutt, Strahan, and Tehranian (2011) studied how banks managed the liquidity shock that occurred during the financial crisis of 2007-2009 by adjusting their cash holdings and other liquid assets, as well as how these efforts to weather the storm affected credit availability. The authors then built a panel dataset from the quarterly Federal Financial Institutions Examination Council (FFIEC) Call Reports, which all regulated commercial bank files with their primary regulator. When the results were aggregated they found find that most of the decline in bank credit production during the height of the crisis could be explained by liquidity risk exposure.

Without comparing, but using machine learning techniques, Moradi and Rafiei (2019) used a fuzzy inference system to create a rule base using a set of uncertainty predictors. First, the authors trained an Adaptive Network-based Fuzzy Inference System (ANFIS) using monthly data from a customer profile dataset. Then, using the newly defined factors and their underlying rules, a second round of assessment began for the fuzzy inference system.

Papers were also found in which the methodology proposed by the authors themselves could not be categorized. These proposed techniques were not applied into any known database, and therefore they were not able to be compared. For example, Laeven, Levine and Michalopoulos (2015) proposed a technique through which entrepreneurs could earn profit by inventing better goods and profit-maximizing financiers arise to screen them. The model has two novel features: financiers engage in the costly but potentially profitable process of innovation (they can invent better methods for screening entrepreneurs); every screening process becomes less effective as technology advances. The model predicted that technological innovation and economic growth would eventually stop unless financiers started to innovate. Koopman, Kraussl, Lucas, and Monteiro (2009) used an intensity-based framework to study the relation between macroeconomic fundamentals and cycles in defaults and rating activity. By using Standard and Poor's U.S. corporate rating transition over the period 1980-2005, the authors estimated the default and rating cycle from micro data. They were able relate the business cycle, bank lending conditions, and financial market variables. They found that the macro variables appeared to explain part of the default cycle.

Wang et al. (2012) proposed an approach called RSFS (Random Subset Feature Selection), used for feature selection based on rough set and scatter search. In RSFS, conditional entropy is regarded as the heuristic to search for the optimal solutions. Two credit datasets in the UCI database were used to demonstrate the competitive performance of RSFS, which consisted in three credit models including Artificial Neural Networks (ANN), J48 Decision Trees (J48 DT), and Logistic Regression (LR). The experimental results showed that RSFS has a superior performance in saving the computational costs and improving classification accuracy. The last work, which had a proposed, untested technique, was a hybrid classification method based on rough sets, partial conditional probability assessments, and fuzzy sets. Their approach improved the classification capabilities of standard rough sets in credit risk (Capotorti and Barbanera, 2012).

There were papers which didn't have a technique itself or did not mention any throughout their content. Their applications varied, such as providing insight in credit risk. It might have helped practitioners to stay abreast of advancements in predictive modeling. From an academic point of view, the study provided an independent assessment of recent scoring methods and offered a new baseline to which future approaches can be compared (Lessmann, Baesens, Seow, and Thomas, 2015). Others assess the relationship between financial innovation, bank growth and fragility, and economic growth. The authors found that different measures of financial innovation are associated with faster bank growth, but also higher bank fragility and worse bank performance during the crisis (Beck, Chen, Lin, and Song, 2016). A discussion about inputs for direct marketing models was provided by describing the various types of used data, by determining the significance of the data, and by addressing the issue of selection of appropriate data (Bose and Chen, 2009). Authors also investigated the most influential evidence on the moral hazard effect of securitization, based on discontinuities in lender behavior at certain credit cores (Bubb and Kaufman, 2014).

Between the papers which did not compare results, there were the ones in which actual machine learning or statistic-based methods were applied to analyze the reasons why banks securitized on a large scale using the LR model, thus leading to indicate that liquidity and the search for improved performance are decisive factors in securitization (Cardone-Riportella, Samaniego-Medina, and Trujillo-Ponce, 2010). Some authors also examined state-level banking industry, as well as region economic determinants of non-performing loans for commercial banks and savings institutions by using both fixed effects and dynamic Generalized Method of Moments (GMM) estimations (Ghosh, 2015). Works also described an empirical study of instance sampling in predicting consumer repayment behavior, which evaluated the relative accuracies of logistic regression, discriminant analysis, DT (Decision Trees) and ANN on datasets created by gradually under- and over-sampling the good and bad, respectively (Crone and Finlay, 2012).

Another paper that applied linear programming was developed by Kwak, Shi, and Kou (2012). The authors proposed a Multiple Criteria Linear Programming (MCLP) method to predict bankruptcy, using Korean bankruptcy data after the 1997 financial crisis. The results of the MCLP approach in the Korean bankruptcy prediction study show that their method performed as well as traditional multiple discriminant analysis or logit analysis by using only financial data. In addition, this model's overall prediction accuracy is comparable to those of decision tree or support vector machine approaches.

In García, Marqués, and Sánchez, (2012) the authors did not use techniques to solve the credit risk problem. Their assessment involved dealing with the presence of noise and outliers in the training set, which may strongly affect the performance of the prediction model. Therefore, they systematically investigated whether the application of filtering algorithms leads to an increase in accuracy of instance-based classifiers in the context of credit risk assessment.

Machine Learning Applications

From the papers which used mainly machine learning techniques, Chi and Hsu (2012) selected important variables by using GA (Genetic Algorithm) to combine the bank's internal scoring model with the external credit bureau model to construct a dual scoring model for credit risk management. The results showed that the predictive ability of the dual scoring model outperforms both one-dimensional behavioral scoring and credit bureau scoring models.

Among other applications with machine learning techniques were Self-Organizing Maps (SOM), for a compact visualization of the complex behaviors in financial statements, in order to analyze the financial situation of companies over several years through a two-step clustering process (Chen, N., Ribeiro, Vieira, and Chen, A., 2013). ANN were also found among the selected papers, either to focus on enhancing credit risk models in three aspects –(i) optimizing the data distribution in datasets using a new method called Average Random Choosing; (ii) comparing effects of training-validation-test instance numbers; and (iii) finding the most suitable number of hidden units (Zhao et al., 2015)–, or combined with other techniques such as Support Vector Machines (SVM), K-Nearest Neighbours (kNN), and DT to provide some guidelines for the usage of databases, data splitting methods, performance evaluation metrics, and hypothesis testing procedures (García, Marqués, and Sánchez, 2014). And, finally, an application where a model based on binary quantile regression was proposed, using Bayesian estimation, called Bayesian Binary Quantile Regression (BBQR). The authors pointed out the distinct advantages of the latter approach: (i) the method provided accurate predictions of which customers may default in the future, (ii) the approach provided detailed insight into the effects of the explanatory variables on the probability of default, and (iii) the methodology was ideally suited to build a segmentation scheme of the customers in terms of risk of default and its corresponding uncertainty (Miguéis, Benoit, and Van Den Poel, 2013).

As for statistic-based techniques, there were probabilistic methods such as CPH (Cox Proportional Hazards) to reduce form models for credit risk in corporate lending, where the authors exploited the parallels between behavioral scores and ratings ascribed to corporate bonds (Malik and Thomas, 2010). Methods where the dependent variable was limited were also found, such as in LR for analyzing whether microfinance institutions can benefit from credit risk, been successfully adopted in retail banking (Van Gool, Verbeke, Sercu, and Baesens, 2012), or even a Probit Regression (PR) for suggesting that small firms low risk credit contracts with liquid collateral, which are their primary source of credit (Zambaldi, Aranha, Lopes, and Politi, 2011).

Considering the papers that used mainly AI (boosting techniques are not included on this section), there were works which aimed at the case of customers' default payments and compared the predictive accuracy of default probability (Yeh and Lien, 2009).

Other authors who described a credit risk evaluation system that used three supervised ANN models, each testing nine learning methods based on Back Propagation (BP) learning algorithm (Khashman, 2010), or even developed a heuristic algorithm, Hybrid Genetic Algorithm Neural Network (HGANN), which was used to identify an optimum feature subset and increase the classification accuracy in credit risk assessment (Oreski and Oreski, 2014).

Among the papers which used AI and involved these techniques as their best performance, then again, not considering the ones which applied boosting techniques, there were authors who proposed a three stage hybrid Adaptive Neuro Fuzzy System (ANFIS) credit risk model, which is based on statistical techniques and Neuro Fuzzy. Its performance was compared with conventional and commonly utilized models and showed its superiority (Akkoç 2012).

Also using AI and other techniques such as LR (Logistic Regression) and a hybrid algorithm, Cleofas-Sánchez, García, Marqués, and Sánchez (2016) explored hybrid associative memory with translation for default prediction. The performance of the hybrid associative memory with

translation is compared to four traditional neural networks, a support vector machine, and a logistic regression model in terms of their prediction capabilities.

Zhou, Lai, and Yu (2010) developed their research around testing 16 different methods and financial services datasets from companies in England. The authors found that Least Square Support Vector Machines (LSSVM) were the best performance method among other AI, statistics, and boosting techniques (combined or not). Also testing a variety of techniques, Loterman, Brown, Martens, Mues, and Baesens, (2012) showed a comparison of a total of 24 techniques using six real-life loss datasets from major international banks, where both LSSVM and ANN had the best overall performances.

Studying feature selection, Oreski, S., Oreski, D., and Oreski, G. (2012) investigated the extent to which the total data owned by a bank can be a good basis for predicting the borrower's ability to repay the loan on time, by using techniques such as Genetic Algorithm Neural Networks (GANN), Feature Selection Neural Networks (FSNN) and Generic Model for Parameters Optimization of the Artificial Neural Network (NNGM), where GANN had better accuracy than the others. Peng, Wang, Kou, and Shi, (2011) developed a two-step approach to evaluate classification algorithms for financial risk prediction. This method constructed a performance score to measure the performance of classification algorithms and introduced three Multiple Criteria Decision Making (MCDM) methods to provide a final ranking of classifiers. An empirical study was designed to assess various classification algorithms over seven real-life credit risk and fraud risk datasets from six countries where NBC (Naıve Bayes Classifiers) had better performance than the other tested methods.

Chen, Ma, and Ma (2009) proposed a hybrid support vector machine technique based on three strategies: (1) using Classification and Regression Trees (CART) to select input features, (2) using Multivariate Adaptive Regression Splines (MARS) to select input features, (3) using grid search to optimize model parameters. The authors tested their methods on a local bank and found that the hybrid of SVM + MARS was the best option to assess credit risk.

Having built several non-parametric credit risk models based on Multilayer Perceptron (MLP) and benchmarks of their performance against other models which employ the traditional Linear Discriminant Analysis (LDA), Quadratic Discriminant Analysis (QDA) and LR techniques, based on a sample of almost 5500 borrowers from a Peruvian microfinance institution, the results presented in Blanco et al. (2013) showed that NN (Neural Networks) models outperform the other three classic techniques both in terms of area under the receiver-operating characteristic curve (AUC) and as misclassification costs.

Harris (2015) investigated the practice of credit risk and introduced the use of the Clustered Support Vector Machine (CSVM) for credit scorecard development, comparing it with methods such as SVM, LinR (Linear Regression), LR, DT and ANN into datasets from Germany and Barbados. From among these techniques, CVSM was found to have a better performance than the rest of the techniques. There were works where four different types of hybrid models were compared by 'Classification + Classification', 'Classification + Clustering', 'Clustering + Classification', and 'Clustering + Clustering' techniques, respectively, applied on a Taiwan dataset where it was found that a Classification + Classification (LR + ANN) had a better performance than the other hybrids (Tsai and Chen, 2010).

Based on UK data from major retail credit cards, Bellotti and Crook (2012) built several models of Loss Given Default (LGD) based on account level data, including Tobit, a decision tree model, and a Beta and fractional logit transformation. The authors found that OLS (Ordinary Least Squares Estimation) models with macroeconomic variables perform best for forecasting LGD at the account and portfolio levels on independent hold-out data sets.

Lin (2009) proposed a new approach with three kinds of two-stage hybrid models of LR+ANN to explore if the two-stage hybrid model outperformed the traditional ones, and to construct a financial distress warning system for the banking industry in Taiwan. The results found factors for observable and total loans, allowance for doubtful accounts recovery rate, and interest-sensitive assets to liabilities ratio to be significantly related to the financial distress of banks in Taiwan. In the prediction of financially distressed, two-stage hybrid model (LR+ANN) giving the best performance with an 80% accuracy.

A work was also found which proposed a new type of multiple criteria CBR method for Binary Business Failure prediction (BFP) with Similarities to Positive and Negative Ideal Cases (SPNIC). The results indicate that this new CBR forecasting method can produce significantly better short-term discriminate capability than comparative methods, except for SVM, which had the best performance among the tested methods (Li, Adeli, Sun, and Han, 2011).

Wang and Ma (2012) also applied the SVM technique. Their research proposes a new hybrid ensemble approach called RSB-SVM, which is based on two popular ensemble strategies, i.e., bagging and random subspace, and uses a Support Vector Machine (SVM) as base learner. The enterprise's credit risk dataset, which included financial records from 239 companies and was collected by the Industrial and Commercial Bank of China, was selected by the authors to demonstrate the effectiveness and feasibility of the proposed method.

Other works in which the best performance involved SVM had their research either based on a comprehensive experimental comparison study over the effectiveness of learning algorithms such as ANN back propagation, Extreme Learning Machine (ELM), I-ELM, and SVM over a dataset consisting of real financial data from two corporate credit ratings not specified by the authors (Zhong, Miao, Shen, and Feng, 2014). Another one evaluated the performance of seven individual prediction techniques when used as members of five different ensemble methods, in order to suggest appropriate classifiers for each ensemble approach in the context of credit risk (Marqués, García, and Sánchez, 2012).

Some even tested only different models of SVM such as the work developed by Harris (2013), who had the research methodology based on credit-scoring models built using Broad (less than 90 days past due) and Narrow (greater than 90 days past due) default definitions.

Khashman (2009) presented a credit risk evaluation system that uses a NN model based on the back-propagation learning algorithm. Two types of ANN were tested: the first, using single hidden layers; and the second one, using two hidden layers. Analyzing the results, the author showed that the single hidden layer ANN outperformed the other method. This same author also tested six architectures of Emotional Back Propagation (EmBP) and six other ANN to investigate the efficiency of Emotional Neural Networks (EmNN) and compare their performance to conventional NNs when applied to credit risk evaluation. It was found that one of the ANN's tested architectures outperformed all the other applications (Khashman, 2011).

In Zhou, Jiang, Shi, and Tian, (2011) discussed that data mining and machine learning techniques such as SVM have been widely discussed in credit risk evaluation. The authors compared DM techniques against an optimization algorithm (kernel-based learning method called kernel affine subspace nearest point, KASNP) where they found that KASNP is an unconstrained optimal problem whose solution can be directly computed.

Iturriaga and Sanz (2015) developed a NN model to study the bankruptcy of US banks, taking into account the specific features of the recent financial crisis. The authors combined MLP and SOM to provide a tool that displays the probability of distress up to three years before bankruptcy occurs. Based on data from the Federal Deposit Insurance Corporation between 2002 and 2012, their results showed that failed banks are more concentrated in real estate loans and have more provisions. Thus, the best method to predict a non-failed bank would be ANN; to predict a failed one, SVM would be the best.

Research tried to describe what is a good or bad credit by evaluating it. The authors proposed three link analysis algorithms based on the process of SVM, to estimate an applicant's credit, so as to decide whether a bank should provide a loan. The proposed algorithms have two major phases which are called input weighted adjustor and class by SVM-based models. Among the four machine learning techniques tested, the authors found the best performance for their problem in using Hub Authority Ranking Applicants (HARA) (Xu, Zou, and Wang, 2009).

Hens and Tiwari (2012) proposed a strategy to reduce the computational time for credit risk. In this approach, the authors used SVM incorporated with the concept of reduction of features by using F score and taking a sample, instead of taking the whole dataset to create the credit risk model. The authors then compared their result with the one obtained from other methods. Their credit risk model was found to be very competitive with others due to its accuracy, as well as the fact that it takes both less computational time and that the Genetic Programing algorithm (GP) had the best performance.

Aiming to compare a new algorithm (recursive feature extraction with support vector machines, RFE-SVM) with well-known ML techniques, Derelioğlu and Gurgen (2011) proposed a knowledge discovery method that uses a MLP-based neural rule extraction (NRE) approach for credit risk analysis (CRA) of real-life small and medium enterprises (SMEs) in Turkey. In the first stage, the feature selection was achieved with the decision tree (DT), and recursive feature extraction with support vector machine (RFE-SVM) methods. The feature extraction was performed with factor analysis (FA) and principal component analysis (PCA). Then, the Continuous/Discrete Rule Extractor via Decision Tree Induction (CRED) algorithm is used to extract rules from the hidden units of a MLP for knowledge discovery.

Approaching different SVM methods, Danenas and Garsva (2015) combined CSVM, SVM and LSVM with external evaluation and sliding window testing, with focus on applications on larger datasets. The results showed that the CSVM technique had outperformed the others. In Chang and Yeh (2012), two experimental credit datasets were used to show the accuracy rate of the AINE classifier, applying a cross-validation method to evaluate its performance and compare it with other techniques. Experimental results showed that the AINE classifier is more competitive than SVM and hybrid-SVM classifiers.

In Khandani, Kim and Lo (2010), machine-learning techniques were applied to construct nonlinear, nonparametric forecasting models of consumer credit risk. By combining customer transactions and credit bureau data from January 2005 to April 2009 for a sample from a major commercial bank's customers, the authors were able to construct out-of-sample forecasts that significantly improved the classification rates of credit-card-holder delinquencies and defaults, with LR R2's of forecasted/realized delinquencies of 85%.

Hájek (2011) presented the modelling possibilities of NN on a complex real-world problem, i.e., municipal credit rating modelling. Testing ANN, Radial Basis Functions Neural Networks (RBF NN), Probabilistic Neural Networks (ProbNN), Cascade Correlations Neural Networks (CCNN), Group Method of Data Handling (GMDH), SVM, Multivariate Discriminant Analysis (MDA), LR, K-Means, and, finally, Classification Trees (CT), the results showed that the rating classes assigned to bond issuers can be classified with a high accuracy rate using a limited subset of input variable. Furthermore, the best technique for the proposed application would be ProbNN.

Tserng, Lin, Tsai, and Chen (2012) proposed an Enforced SVM-based model (ESVM model) for the default prediction in the construction industry using all available firm-years data in our ten-year sample period to solve the between-class imbalance. The empirical results of this paper show that the ESVM model always outperforms the logistic regression model and is more convenient to use because it is relatively independent of the selection of variables.

In Bijak and Thomas (2012), two-step approaches were applied, as well as a new, simultaneous method, in which both segmentation and scorecards were optimized at the same time: Logistic Trees with Unbiased Selection (LOTUS). For reference purposes, a single-scorecard model was used. The model performance measures were then compared to examine whether there was any improvement due to the used segmentation methods. Both CART and Chi-square automatic interaction detection (CHAID) had the best overall performance among the four tested models.

Koyuncugil and Ozgulbas (2012) also used the CHAID technique, while eveloping a financial early warning system through data mining, and SMEs were classified in 31 risk profiles. They also determined 2 financial early warning signs: profit before tax to owned funds and return on equity.

Also using the ML technique, Khemakem and Boujelbene (2018) used the Synthetic Minority Oversampling Technique (SMOTE). It was used to solve the problem of class imbalance and improve the performance of the classifier. The ANN and DT were designed to predict default risk. Results showed that profitability ratios, repayment capacity, solvency, duration of a credit report, guarantees, size of the company, loan number, ownership structure, and corporate banking relationship duration turned out to be the key factors in predicting default. Also, both algorithms were found to be highly sensitive to class imbalance. However, with balanced data, the decision trees displayed higher predictive accuracy for the assessment of credit risk than artificial neural networks.

As for mainly AI techniques tested in research from the last two years, the work developed by Li, Tian, Li, Zhou, and Yang (2017) was found. This paper extended studies in two main ways: firstly, it proposed a method involving machine learning to solve the reject inference problem; secondly, the Semi-Supervised Support Vector Machines (SSVM) model was found to improve the performance of scoring models compared to the industrial benchmark of LR.

In Bequé and Lessmann (2017), the authors explored the potential of ELM for consumer credit risk management. They found that ELM possesses some interesting properties, which might enable them to improve the quality of model-based decision support. To test this, they empirically compared ELM to established scoring techniques according to three performance criteria: ease of use, resource consumption, and predictive accuracy. The mathematical roots of ELM suggest that they are especially suitable as a base model within ensemble classifiers.

Kvamme, Sellereite, Aas, and Sjursen (2018) investigated, by using ANN, how transaction data can be used to assess credit risk. In a joint research with Norway's largest financial service group, DNB, they used transaction data to predict mortgage defaults. In 2012, the average Norwegian made 323 card transactions, where 71% of the value transferred was through debit payments. Hence, transactional data provided a useful description of user behavior, and subsequently consumer credit risk. Therefore, they predicted mortgage default by applying Convolutional Neural Networks (CNN) to consumer transaction data.

The main goal of Tavana, Abtahi, Caprio, and Poortarigh (2018) was the design of a system capable of warning about probable liquidity risk based only on raw data available in the bank's book or balance sheet without any predefined function. The implementation of two intelligent systems (ANN and Bayesian Neural Networks, BNN) comprised several algorithms and tests for validating the proposed model. A real-world case study was presented to demonstrate applicability and exhibit the efficiency, accuracy, and flexibility of data mining methods when modeling ambiguous occurrences related to bank liquidity risk measurement.

Another paper dealt with feature selection for credit risk assessment. Lahmiri (2016) aimed to compare several predictive models that combined feature selection techniques with data mining classifiers in the context of credit risk assessment, namely in terms of accuracy, sensitivity, and specificity statistics. The selected features werw used to train the SVM classifier, backpropagation neural network, radial basis function neural network, linear discriminant analysis and naive Bayes classifier.

Finally, the last paper that applied and had an AI method involved in its best performance was developed by Antonakis and Sfakianakis (2009). The authors examined the effectiveness of NBR as a method for constructing classification rules (credit scorecards) in the context of screening credit applicants (credit risk). For this purpose, the study used two real-world credit risk datasets to benchmark NBR against LDA, logistic regression analysis, k-nearest neighbours, classification trees, and neural networks. The results showed that, although NBR is definitely a competitive method, it was outperformed by CT and ANN applications.

Ensemble Techniques

Among the papers which used machine learning techniques, there were also the ones which showed that ensemble techniques were differential in order to make one method better than the other. For instance, Wang, Hao, Ma, and Jiang (2011) conducted a comparative assessment of the performance of three popular ensemble methods, i.e., Bagging, Boosting, and Stacking, based on four base learners, namely LR, DT, ANN, and SVM. Their experimental results revealed that the three ensemble methods can substantially improve individual base learners. Regarding the Australian database, the best performance was obtained by LR ,combined with Bagging. On the Chinese one, it was DT and Bagging, and only for the German database, the best performance method was SVM without ensemble techniques.

Twala (2010) explored the predicted behavior of five classifiers for different types of noise in terms of credit risk prediction accuracy, and how such accuracy could be improved by using classifier ensembles. Benchmarking results on four credit datasets and a comparison with the performance of each individual classifier on predictive accuracy at various attribute noise levels were presented. The experimental evaluation showed that the best overall performance was attributed to DT combined with feature selection algorithms and boosting techniques. As in Wang, G., Ma, Huang, and

Xu, (2012), two dual strategy ensemble trees were proposed: RS-Bagging DT and Bagging-RS DT, which were based on two ensemble strategies (Bagging and random subspace) in order to reduce the influence of noise data and redundant data attributes, as well as to get a relatively higher classification accuracy. Two real world credit datasets were selected to demonstrate the effectiveness and feasibility of proposed methods. Experimental results revealed that single DT gets the lowest average accuracy among five single classifiers, but, when combined with Bagging, things would go differently.

In Finlay (2011), the performance of several multiple classifier systems was evaluated in terms of their ability to correctly classify consumers as good or bad credit risks. Empirical results suggest that some multiple classifier systems deliver significantly better performance than the single best classifier, where ET Boost had better performance than others. Also assessing machine learning techniques for credit risk analysis, a research went one step beyond by introducing composite ensembles that jointly use different strategies for diversity induction. Accordingly, the combination of data resampling algorithms (Bagging and AdaBoost) and attribute subset selection methods (random subspace and rotation forest) for the construction of composite ensembles was explored, with the aim of improving prediction performance, where Bagging combined with RF had the best tested performance (Marqués et al., 2012).

The research developed by Florez-Lopez and Ramon-Jeronimo (2015) introduced an ensemble approach based on merged decision trees, the Correlated-Adjusted Decision Forest (CADF), to produce both accurate and comprehensible models. As its main innovation, this proposal explored the combination of complementary sources of diversity as mechanisms to optimize model structure, which led to a manageable number of comprehensive decision rules without sacrificing performance. The approach was evaluated in comparison to individual classifiers and alternative ensemble strategies (gradient boosting and random forests), and the best performance was developed by SVM and Gradient Boosting. However, empirical results suggested CADF might be an encouraging solution for credit risk problems, being able to compete in accuracy with more complex proposals while producing a rule-based structure directly useful for managerial decisions.

And finally, the last research which happened to involve ensemble techniques was developed by Abellán and Castellano (2017). The authors showed that a very simple base classifier attained a better trade-off in some aspects of interest for this type of studies, such as accuracy and area under the ROC curve (AUC). The AUC measure could be considered more appropriate in this ground, where different type of errors have different costs or consequences. The results presented this simple classifier as an interesting choice to be used as a base classifier in ensembles for credit risk and bankruptcy prediction, proving that individual performance of a classifier is not the only key point to be selected for an ensemble scheme. In six different datasets, a diversity of results were obtained. For instance, the best performance ensemble for the Australian database was MLP combined with Random Subspace; for the German one, LR with DECORATE; as for the Japanese, LR combined with Bagging; for the the Iranian, C4.5 (C4.5 Decision Tree) with Rotation Forest; for the Polish dataset, MLP with Bagging; and finally, for UCSD, the CDT method combined with Rotation Forest.

Now, as for the papers collected after the first selection, Xia Y., Liu C., Li, and Liu N. (2017) proposed a sequential ensemble credit risk model based on a Variant of Gradient Boosting Machine (i.e., Extreme Gradient Boosting, XGBoost). The tested methods were Tree-Structured Parzen Estimator (TPE), Random Search (RS), Grid Search (GS), Manual Search (MS), XGBoost, Gradient Boosting Decision Tree (GBDT), ANN, DT, LR, RF, and SVM.

Barboza, Kimura and Altman (2017) tested models to predict bankruptcy one year in advance, and compare their performance with results from SVMLin, SVM RBF, MDA, LR, ANN, Boosting, Bagging, and RF by using data from 1985 to 2013 on North American firms. Comparing the best models, with all predictive variables, the ensemble with RF led to an 87% accuracy, whereas logistic regression and linear discriminant analysis led to 69% and 50%, respectively, in the testing sample.

Another case where an ensemble technique combined with rule-based machine learning happened to have the best results is shown by Sun, Lang, Fujita, and Li (2018). In that paper, different times of iteration for base DT classifier training, new positive (high-risk) samples were produced to different degrees by SMOTE with Differentiated Sampling Rates (DSR), and different numbers of negative (low-risk) samples are drawn with replacement by Bagging with DSR. The experimental results indicate that DTE-SBD (Decision Tree Ensemble based on SMOTE, Bagging and DSR) significantly outperforms the other five models and is effective for imbalanced enterprise credit evaluation.

Also among the papers was the introduction of Deep-Belief Network (DBN) as a credit rating algorithm to generate fast and accurate individual classification results, compared with more traditional methods such as SVM, MLP and Multinomial Logistic Regression (MLR) (Luo, Wu, and Wu, 2017). The goal of the paper was to provide a set of descriptive results and tests that lay a foundation for future theoretical and empirical work on DBN in credit risk in Credit Default Swap (CDS) markets. The authors investigated the performances of different credit risk models by conducting experiments on a collection of CDS data.

Another research about XGBoost was also found, this time as CSXGBoost (Cost-Sensitive Extension of XGboost). In the work, developed by Xia, Liu C., and Liu N. (2017). The authors proposed a cost-sensitive boosted tree loan evaluation model by incorporating cost-sensitive learning and XGBoost to enhance the capability of discriminating potential default borrowers. Therefore, a portfolio allocation model that converts the portfolio optimization problem into an integer linear programming was proposed as a decision support system for unprofessional lenders.

Xia, Liu, Da, and Xie (2018) propose a novel heterogeneous

ensemble credit model (RF, XGBoost, and MV, Majority Voting) that integrated the Bagging algorithm with the stacking method. The proposed model differs from the extant ensemble credit models in three aspects: pool generation, selection of base learners, and trainable fuser. To confirm the efficiency of this proposed approach, a wide range of models, including individual classifiers and homogeneous and heterogeneous ensemble models, were introduced as benchmarks.

Rule-Based Machine Learning

Besides ensemble and AI techniques, there were papers which had a rule-based machine learning algorithm applied in its research, such as the one by Huysmans, Dejaeger, Mues, Vanthienen, and Baesens (2011), who, based on a number of observations, constructed a decision table model that allowed the analysts to provide classifications or predictions for new observations. The Decision Table (Dtab) algorithm was compared with the DT technique. The first one had a superior performance. As for DT as the best performance technique, we found the research of Paleologo, Elisseeff and Antonini (2010), where several classification techniques were shown to perform well on credit risk – e.g. support vector machines. While the investigation of better classifiers is an important research topic, the specific methodology chosen in real-world applications has to deal with the challenges arising from the data collected within the industry.

Also, algorithms based on swarm optimization, such as Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO), were also found among the selected papers. A study used two nature-inspired methods (ACO and PSO) for this credit risk assessment. The modelling context was developed, and its performance of the methods tested in two financial classification tasks involving credit risk assessment and audit qualifications. ACO was proposed in this study for solving this feature subset selection problem. These two nature-inspired techniques had the best performance among the others (Tabu Search, TS, and GA).

Nature-inspired methods are approaches used in various fields for the solution for a number of problems. Marinaki, Marinakis and Zopounidis (2010) used a nature-inspired method, namely Honey Bee Mating Optimization (HBMO), that was based on the mating behavior of honey bees for a financial classification problem. Being compared with PSO, ACO, GA, and TS, the HBMO method had the best performance for the analyzed problem.

Vukovic, Delibasic, Uzelac, and Suknovic (2012) proposed a Case-Based Reasoning (CBR) model that used preference theory functions for similarity measurements between cases. As it is hard to select the right preference function for every feature and set the appropriate parameters, a genetic algorithm was used to choose the right preference functions, or more precisely, to set the parameters of each preference function, such as setting attribute weights. The proposed model was compared to the well-known k-NN model, based on the Euclidean distance measure. It was evaluated on three different benchmark datasets, while its accuracy was measured with 10-fold cross-validation tests. The experimental results show that the proposed approach can, in some cases, outperform the traditional k-NN classifier.

In Kruppa, Schwarz, Arminger, and Ziegler (2013) a general framework was presented to estimate individual consumer credit risks by means of machine learning methods. Since a probability is an expected value, all nonparametric regression approaches which are consistent for the mean are consistent for the probability estimation problem. Among others, random forests RF, KNN, and Bagged k-Nearest Neighbors (bagged bNN) belong to this class of consistent nonparametric regression approaches. From the tested algorithms, RF had a better development and performance than the rest of the methods.

Zhou, Lu, and Fujita (2015) investigated the performance of different financial distress prediction models with feature selection approaches based on domain knowledge or data mining techniques. The empirical results showed that there is no significant difference between the best classification performance of models with feature selection guided by data mining techniques and the ones guided by domain knowledge.

Sánchez-Lasheras, de Andrés, Lorca, and de Cos Juez (2012) proposed a new approach to firm bankruptcy forecasting. Their proposal was a hybrid method in which sound companies were divided in clusters using SOM. Each cluster was then replaced by a director vector which summarized all of them. Once the companies in clusters had been replaced by director vectors, the authors estimated a classification model through MARS.

Considering now the second batch of papers from the past two years, Lanzarini, Villa Monte, Bariviera, and Jimbo Santana (2017) presented an alternative method that could generate rules that work not only on numerical attributes but also on nominal ones. The key feature of this method, called Learning Vector Quantization and Particle Swarm Optimization (LVQ + PSO), was their finding of a reduced set of classifying rules. Their findings indicate that the reduced quantity of rules made this method useful for credit officers aiming to make decisions about granting a credit.

Statistical Methods Applications

As for the last portion of the analyzed papers, there were the ones in which statistical methods were involved in achieving the best performance. Initially, there were papers which did not compare methods, such as Louzis, Vouldis, and Metaxas (2011); Tinoco and Wilson (2013); and Ferreira, Santos, Marques, and Ferreira J. (2014). The first work was motivated by the hypothesis that both macroeconomic and bank-specific variables have an effect on loan quality and that these effects vary between different loan categories. By applying GMM, the results showed that, for all loan categories, NPLs in the Greek banking system can be explained mainly by macroeconomic variables (GDP, unemployment, interest rates, and public debt) and management quality. In Tinoco and Wilson (2013), using a sample of 23,218 company-year

observations of listed companies during the period 1980-2011, the paper investigated empirically, using LR, the utility of combining accounting, market-based and macro-economic data to explain corporate credit risk. The paper developed risk models for listed companies that predict financial distress and bankruptcy. In Ferreira et al. (2014), the authors proposed a methodological framework allowing for the readjustment of trade-offs within risk evaluation criteria, considered of extreme importance in the lending decision process of mortgage loans. Measuring attractiveness is performed with a categorical based evaluation technique (MACBETH) to a pre-established structure of credit-scoring criteria for mortgage lending risk evaluation. This pre-established structure was used by one of the largest banks in Portugal and the framework allowed the authors to provide credit experts who participated in the study with a more informed, transparent and accurate mortgage lending risk evaluation system.

Following the papers which had statistical methods as best performance algorithms, there were the ones which actually compared different techniques. In Yu, Wang, and Lai (2009) a novel intelligent-agent-based fuzzy Group Decision Making (GDM) model was proposed as an effective Multicriteria Decision Analysis (MCDA) tool for credit risk evaluation. For comparison, the authors also tested the original GDM, SVMR (Support Vector Machines Regression), RBF NN, Back Propagation Neural Networks (BPNN), LR, and LinR. Finally, the authors found that the novel method had the best performance among the tested algorithms. Andrés, Lorca, de Cos Juez, and Sánchez-Lasheras (2011) proposed a hybrid system which combines fuzzy clustering and MARS. Both models were especially suitable for the bankruptcy prediction problem, due to their theoretical advantages when the information used for the forecasting is drawn from company financial statements. The authors tested the accuracy of their approach in a real setting consisting of a database made up of 59,336 non-bankrupt Spanish companies and 138 distressed firms which went bankrupt during 2007, and found that the hybrid Fuzzy C-Means, combined with MARS, had the best performance.

Six papers were found in which LR was the best technique. One of them assessed LR and compared it with SVM, LDA and kNN on a large credit database (Bellotti and Crook, 2009). Another one investigated whether productive inefficiency measured as the distance from the industry's 'best practice' frontier is an important *ex-ante* predictor of business failure; there was research that tested DEA (Data Envelopment Analysis) and LR as its methodology (Psillaki, Tsolas, and Margaritis, 2010). Using data mining to improve the assessment of credit worthiness using credit risk models, Yap, Ong and Husain (2011) compared the classification performance of the credit scorecard model, the LR model, and the DT model. The classification error rates for credit scorecard model, logistic regression and decision tree were 27.9%, 28.8% and 28.1%, respectively.

Kou, Peng, and Wang (2014) presented an MCDM-based (Multiple Criteria Decision Making) approach to rank a selection of popular clustering algorithms in the domain of financial risk analysis. An experimental study is designed to validate the proposed approach using three MCDM methods, six clustering algorithms, and eleven cluster validity indices from three real-life credit risk and bankruptcy risk datasets. The results demonstrate the effectiveness of MCDM methods in evaluating clustering algorithms and indicate that the repeated bisection method leads to good 2-way clustering solutions on the selected financial risk datasets.

Tong, Mues and Thomas (2012), estimated a mixture cure model predicting time to default on a UK personal loan portfolio, and compare its performance against the Cox Proportional Hazards (CPH) method and standard logistic regression. Following their experimental results, the authors found that standard LR performed better than CPH. Lessmann and Vob (2009) proposed a hierarchical reference model for SVM-based classification in this field. The approach balances the conflicting goals of transparent, yet accurate models, and compares favorably to alternative classifiers in a large-scale empirical evaluation in real-world customer relationship management applications. Among all tested models (RBF SVM, SVM, LR and CART), the LR algorithm had the better performance.

The last paper which had LR as its best performing algorithm was developed by Bekhet and Eletter (2014), where two credit risk models using data mining techniques to support loan decisions for the Jordanian commercial banks were proposed. For this research, algorithms such as LR and RBF NN were tested; the first one had better performance than the other.

Tsai, Lin, Cheng, and Lin P.(2009), constructed the consumer loan default predicting model by conducting an empirical analysis on the customers of unsecured consumer loans from a certain financial institution in Taiwan, and adopted the borrower's demographic variables and money attitude as real-time discriminant information. Furthermore, the authors used four predicting methods, such as Discriminant Analysis (DA), LR, ANN and DEA–DA, to compare their suitability. The results showed that DEA–DA and NN possessed better predicting capability, with DEA-DA being better than the second one. Thus, they proved to be the optimal predicting models that this study was longing for.

In Wu, Olson, and Luo (2014), three different approaches were used: artificial intelligence (ANN); rule-based machine learning (DT) and statistical models (LR). The paper described and demonstrated a model to support risk management of accounts receivable. Accuracy results of this model were presented, enabling accounts receivable managers to confidently apply statistical analysis through data mining to manage the risk.

Zhang, Gao, and Shi (2014) proposed a novel Multi-Criteria Optimization Classifier based on Kernel, Fuzzification, and Penalty factors (KFP-MCOC). Firstly, a kernel function was used to map input points into a high-dimensional feature space. Then an appropriate fuzzy membership function was introduced to MCOC and associated with each data point in the feature space, and the unequal penalty factors were added to the input points of imbalanced classes. The experimental results of credit risk evaluation and their comparison with MCOC, SVM and fuzzy SVM showed that KFP-MCOC could

enhance the separation of different credit applicants, the efficiency of credit risk scoring, and the generalization of predicting the credit rank of a new applicant.

Dong, Lai and Yen (2010), tried to improve the prediction accuracy of logistic regression by combining it with random coefficients. The LRR model showed to improve LR prediction accuracy without sacrificing desirable features. Finally, the last research to be analyzed in this paper was developed by Zhu et al. (2013), where the objective was to put forward a classification approach named Classification Technique for Order Preference by Similarity to Ideal Solution (C-TOPSIS). It is based on the rationale of Technique for Order Preference by Similarity to Ideal Solution TOPSIS), which is famous for reliable evaluation results and quick computing processes, and it is easy to understand and use. In comparison with 7 popular approaches on 2 widely used UCI credit datasets, C-TOPSIS ranked 2nd in accuracy, 1st in complexity, and 1st rank in interpretability. Only C-TOPSIS ranked among the top 3 in all the three aspects, which verified that C-TOPSIS could balance them well.

Considering now the second search of papers (from the past 2 years) where Statistical methods had better performance than the others compared within the research, Maldonado, Bravo, López, and Pérez (2017) proposed a profit-driven approach for classifier construction and simultaneous variable selection based on SVMLin. Their proposal incorporates a group penalty function in the SVM formulation in order to simultaneously penalize the variables that belong to the same group. The framework used algorithms such as Recursive Feature Elimination Support Vector Machines (RFE-SVM), Holdout Support Vector Machines (HOSVM), SVM, Logit Regression, and Fisher Score (FS). It was then studied in a credit risk problem for a Chilean bank, and it led to superior performance with respect to business-related goals.

Finally, Dirick, Claeskens and Baesens (2017) contributed to the existing literature by analyzing ten different data sets from five banks, using both statistical (CPH) and economic evaluation measures (Accelerated Failure Time, AFT), applicable to all considered model types: the "plain" survival models, as well as the mixture cure models.

With that last paper, we are able to bring the content analysis from all the collected research to a close. In the next section, the research questions will be answered, based on the findings of this analysis.

Answering the research questions

As shown at the beginning of this paper, two main questions were asked in order to direct this research. They are discussed below.

Are machine learning techniques being effectively applied in research about credit risk evaluation?

At the start of the analysis, a total of 102 different techniques were found, among them, statistical techniques, boosting methods, MCD makers, multivariate analysis, but mostly machine learning techniques. Those techniques were classified in two main groups: Statistic-Based and Machine Learning, as shown below in Tables 7 and 8, respectively.

Table 7. Summary of Statistic-Based Methods used by the authors, where the acronyms are in Table 4 (legend)

Multivariant Analysisr	**LDA, DA, DLDA, QDA, DQDA, MVA, MARS, MDA**
Dependent Variable Limited	LR, LRA, PR, LD, RiR, RoR, LLR, LRF, LRR, Logit Regression, FS
Probabilistic Methods	MCM, CPH
Non-Linear Regression	GMM
Linear Regression	LinR, BR
Non-Parametric Statistics	DEA
Univariate Analysis	Univariate Analysis
Discriminant Analysis	Discriminant Analysis
Sampling Techniques	SMOTE, DSR
Multiple Criteria Decision Making	MCDM, TOPSIS, PROMETHEE, VIKOR, MCOC, KFP-MCOC, C-TOPSIS

Source: Authors

Table 8. Summary of Machine Learning Techniques Applied to the selected papers where the acronyms are in Table 4 (legend)

Rule-Based Machine Learning	
	DT, DTab, CT, GDM, CART, ID3, EM, RSFS, RT, HARA, HubAvgRA, ATkRA, ACO, PSO, GA, TS, HBMO, HGADSM, bNN, SOM, FSOM, TSOM, RSM, C4.5, GP, 1-NN, CADF, CDT, kNN, Chi-Square Automatic Interaction Detection, RS, GS, MS, GBDT, RF, DTE-SBD, DBN, CSLR-T, CSRF-T, CSLR-SMOTE, CSRF-SMOTE, J48, LVQ+PSO, GPC
Boosting Techniques	ET Boost, Bagging, AdaBoost, Gradient Boosting, Random Subspace, DEC-ORATE, Rotation Forrest, XGBoost, CSXGBoost
Artificial Intelligence	SVM, SVMLin, SVM RBF, ANN, NB, SVMR, RBF NN, BPNN, HGANN, ANFIS, ProbNN, LSSVMRBF, LSSVM-Lin, 1nLSSVMRBF, SVMLin, SVMRBF, NBC, GANN, FSNN, NNGM, MLP, OLS, B-OLS, BC-OLS, CCNN, GMDH, ELM, 1-ELM, EmBP, SHNN, DHNN, AINE, AIRS, SAIS, ESVM, BBQR, Fuzzy C-Means, RFE-SVM, HOSVM, CNN

Source: Authors

From those methods, we were able to identify around 93 machine learning-based techniques, which outnumbered the 36 different statistic-based techniques. Those allowed us to answer this first question, concluding that it is agreeable to assume to the premise which surrounds the high usage of machine learning techniques durin the past ten years of research in Credit Risk Analysis.

Regarding effectiveness, from the 102 papers analyzed, 72 of them used machine learning techniques at some point. From

those 72 papers, 57 involved machine learning or a machine learning hybrid as their best performance technique,. That shows us the effectuality of these techniques and answers our first research question.

Which of these quantitative techniques have been mostly applied over the last ten years of research?

As for the most applied types of quantitative methods, it was found that the use of AI techniques prevailed. Considering Machine Learning techniques, 72 papers used these types of algorithms, and the papers that applied one AI method amounted to 57.

Regarding which AI techniques were used, it was found that ANN was the most applied. This technique appeared 47 times in the papers, either comparing different architectures or different types of ANN. Following ANN, there were the SVM techniques, which appeared 33 times along the review.

Considering Machine Learning methods apart from AI-related ones, e.g. rule-based algorithms, the most used was DT with 16 applications, and kNN followed, appearing in 11 documents. And, finally, concerning boosting techniques, both Bagging and AdaBoost were the most common among the studied papers.

All things considered, the most common technique was ANN, being extensively applied among the found papers, either in machine learning applications or overall techniques.

Conclusions

At the beginning of this research, two questions were presented surrounding credit risk research and the applied methods in order to successfully assess the problem. The first question aimed to determine whether machine learning techniques were being effectively applied in research about credit risk evaluation, and the second one, which of these quantitative techniques have been mostly applied over the last ten years of research.

As expected by the authors, the number of research papers using AI overcame other types of techniques, but more recent papers used less of these methods, suggesting that other approaches are being more accurate than what AI can provide.

Another possible reason why this expectation was not fulfilled happens to concern the filters and techniques; only papers with a higher volume of citations were selected, which could lead to older research. Moreover, this work avoided papers that were used more as a concept review than actually being innovative or showing what actually happens regarding machine learning in credit risk assessment.

An extensive literature review was presented with a protocol including different selection criteria for analyzing papers from three different databases. After the sample was collected, the content analysis was preceeded by a bibliometric review, presenting the journals and keywords. Following this step, the true content of each selected paper was reviewed both in the form of Tables 6 and 7 and the description of the main points of every research.

During the discussion presented above, every amount of different techniques was assessed, and, through that, we were able to find that, not only AI techniques were more applied than the others found, but also ANN is the most common type of AI method found among the papers.

Within the discussion, statistic-based techniques were also assessed, showing that LR is the most common between them. This is reasonable, since the nature of the problem demands for algorithms that are able to classify different client profiles for the decision-maker be able to best select the suiters for the bank credit.

As for future work, other systematic reviews may be developed focusing on AI methods for credit risk assessment, questioning differences between it, and other types of problems involving bank issues. Another option would be to use the reviewed datasets and test different hybrids in order to extend the knowledge barrier of this problem, thus stepping forward in the development of solutions for this type of problem.

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Alkali-activated concretes based on fly ash and blast furnace slag: Compressive strength, water absorption and chloride permeability

Concretos álcali-activados basados en cenizas volantes y escorias siderúrgicas de alto horno: resistencia a compresión, absorción de agua y permeabilidad a cloruros

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ABSTRACT

Concretes based on alkali-activated binders have attracted considerable attention as new alternative construction materials, which can substitute Portland Cement (OPC) in several applications. These binders are obtained through the chemical reaction between an alkaline activator and reactive aluminosilicate materials, also named precursors. Commonly used precursors are fly ash (FA), blast furnace slag (GBFS), and metakaolin. The present study evaluated properties such as compressive strength, rate of water absorption (sorptivity), and chloride permeability in two types of alkali-activated concretes (AAC): FA/GBFS 80/20 and GBFS/OPC 80/20. OPC and GBFS/OPC* concretes without alkali-activation were used as reference materials. The highest compressive strength was observed in the FA/GBFS concrete, which reported 26,1% greater strength compared to OPC concrete after 28 days of curing. The compressive strength of alkali-activated FA/GBFS 80/20 and GBFS/OPC 80/20 was 61 MPa and 42 MPa at 360 days of curing, respectively. These AAC showed low permeability to the chloride ion and a reduced water absorption. It is concluded that these materials have suitable properties for various applications in the construction sector.

Keywords: alkaline activated concrete, fly ash, blast furnace slag, mechanical and permeability properties.

RESUMEN

Los concretos basados en cementantes activados alcalinamente han atraído una atención considerable como nuevos materiales de construcción alternativos que pueden sustituir al cemento Portland (OPC) en diferentes aplicaciones. Estos cementantes se obtienen de la reacción química entre un activador alcalino y materiales aluminosilicatos reactivos, también denominados precursores. Los precursores más habituales son cenizas volantes (FA), escoria de alto horno (GBFS) y metacaolin. El presente estudio evaluó propiedades tales como la resistencia a la compresión, la velocidad de absorción de agua (succión capilar) y la permeabilidad a cloruros de dos tipos de concreto activados alcalinamente (AAC): FA/GBFS 80/20 y GBFS/OPC 80/20. Como materiales de referencia se usaron los concretos OPC y GBFS/OPC*. La mayor resistencia a la compresión se observó en el concreto FA/GBFS, que reportó una resistencia 26,1 % mayor en comparación con el concreto OPC después de 28 días de curado. La resistencia a la compresión de los concretos álcali-activados FA/GBFS 80/20 y GBFS/OPC 80/20 fue de 61 MPa y 42 MPa a los 360 días de curado respectivamente. Estos AAC mostraron una baja permeabilidad al ion cloruro y una absorción de agua reducida. Se concluye que estos materiales presentan propiedades que son adecuadas para diversas aplicaciones en el sector de la construcción.

Palabras clave: concretos de activación alcalina, cenizas volantes, escoria siderúrgica de alto horno, propiedades mecánicas y de permeabilidad.

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Introduction

Portland cement, with an annual production of almost 3 Gt, has become a prevalent material in the construction industry (Juenger, Winnefeld, Provis, and Ideker, 2011; Gao, Shen, Shen, Liu, and Chen, 2016). However, the cement industry is deemed responsible of producing approximately

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2 billion tons/year of CO_2 (Qu, Martin, Pastor, Palomo, and Fernández-Jiménez, 2016), amounting 5% to 7% of the global emissions of anthropogenic CO_2 (Zhang, Han, Yu, and Wei, 2018). Projections for the global demand of Portland cement predict that, within the next 40 years, there will be a two-fold increase in production, reaching 6 Gt/year (Gartner, 2004; Taylor, Tam, and Gielen, 2006). Furthermore, according to Zhang et al. (2018), demand generally exceeds projections, as it occurred in 2010. Thus, it is imperative to act now to reduce any CO_2 emissions related to cement production. This has motivated the scientific community and cement producers to work on different alternatives, which include new raw materials, friendlier production processes, less polluting fuels, an increase in structure lifetime, and the development of new types of cement, among other areas of research activity.

Among the new types of cement, those produced through alkaline activation of aluminosilicate precursors, such as fly ash or metakaolin, which use a chemical activator (e.g., silicates, hydroxides, sulphates or carbonates of sodium, or potassium), emerge as a viable alternative because they offer materials with a low environmental impact. So far, research carried out in the field of alkali-activated cements has shown that these materials generate mechanical and durability properties similar or even superior to those of Portland cements (Pacheco-Torgal, Castro-Gomes and Jalali, 2008a; 2018b; Weil, Dombrowski and Buchawald, 2009; Reddy, Edouard, Sobhan, and Tipnis 2011; Bernal, Mejía de Gutiérrez and Provis, 2012; Pereira et al., 2015; Valencia-Saavedra, Angulo and Mejia de Gutiérrez, 2016; Robayo, Mulford, Munera and Mejía de Gutiérrez, 2016; Tennakoon, Shayan, Sanjayan and Xu, 2017). However, the properties of alkali-activated concretes depend on the type of precursor, the amount and concentration of the alkaline solution used as activator, and the curing temperature. Aluminosilicate precursors with high calcium content are associated with the formation of an Al-substituted C-S-H (C-(A)-S-H) gel, while the reaction product of a precursor with low calcium content is a N-A-S-H gel (Na_2O-Al_2O_3-SiO_2-H_2O) with a three-dimensional structure.

Manjunatha, Radhakrishna, Venugopal, and Maruthi (2014), studied the mechanical behavior of FA/GBFS-based alkali-activated concretes cured at room temperature. The authors reported superior mechanical properties compared to OPC-based concrete. Chi (2016) found a similar behavior and reported high compressive strength at an early age, thus surpassing OPC concrete. Other authors have identified that FA/GBFS-based alkali-activated concretes have a high performance when exposed to aggressive environments (Valencia-Saavedra et al., 2016; Valencia-Saavedra and Mejia de Gutierrez, 2017; Valencia-Saavedra, Mejia de Gutierrez and Puertas, 2020).

Aliabdo, El-Moaty, and Emam (2019) found in 100% GBFS-based alkali-activated concretes that about 90% of its compressive strength and tensile strength was reached at 7 days of curing. These resistances are associated with its low porosity. Abubakr, Soliman, and Diab (2020) evaluated the impact performance of the same type of concrete using different modules of activator solution (Ms= SiO_2/Na_2O ratio) and percentages of Na_2O. They reported that, in comparison with OPC, alkali-activated systems generally had up to 70% and 40% better compressive and tensile strength, respectively. Ms of 1,5 increases the impact energy absorption up to 75%. This agrees with Puertas et al. (2018). Bilim and Atis (2012) -using alkali-activated mortars (GBFS/OPC) with 20%, 40%, 60%, 80% and 100% GBFS, Ms = 0,75, as well as sodium concentrations of 4, 6, and 8%- demonstrated that flexure and compressive strength increase with the GBFS percentage and the concentration of the activator. However, the 100% GFBS-based alkali-activated concretes presented the highest compressive strength. Studies have indicated similar behaviors in GBFS-based alkali-activated systems (Rashad, 2013; Lübeck, Gastaldini, Barin and Siqueira, 2012; Noorliyana et al., 2013). However, these authors used 50% GBFS in OPC-based materials and 70-90% GBFS in binary mixtures with MK and FA. Given the above-mentioned properties, these alkaline-activated cements could partially or totally replace Portland cement in many engineering applications. Among the advantages of this type of cement is the fact that they do not require elevated temperatures for processing because the reactions can typically be carried out at room temperature (Bakharev, Sanjayan and Cheng, 1999; Gebregziabiher, Thomas and Peethamparan, 2015).

In the present study, compressive strength, rate of water absorption (sorptivity), and chloride permeability of two types of alkaline activated concretes (AAC) produced from blast furnace slag and fly ash were evaluated. The results were compared with those of a conventional concrete based on Portland cement (OPC) and a blended cement (GBFS/OPC) without alkaline activation, identified as GBFS/OPC* in the present study. The AAC were: FA/GBFS 80/20, and GBFS/OPC 80/20 which can be classified as alkali-activated blended concretes. It is noted that FA presents a high unburned content (20,67%), which restricts its use in Portland cement-based applications.

Materials and experimental methodology

Materials

The materials used in this study were fly ash (FA), granulated blast furnace slag (GBFS), and Colombian ordinary Portland cement (OPC) for general use. The chemical composition and physical characteristics of these materials are shown in Table 1. The Portland cement used in this work contains an addition of limestone that is related to the loss on ignition percentage found in the chemical composition. There is also a high loss on ignition (LOI) of the fly ash component (20,67%), a value that exceeds the 6% that the ASTM C618 (ASTM International, 2019) recommends for the use of pozzolanic supplementary materials in mixtures with Portland cement. The blast furnace slag used is basic and features a good hydraulic behaviour, according to the indices established by different authors (Hadjsadok, Kenai, Courard, Michel and Khatib, 2012; Pal, Mukherjee and Pathak, 2003; Puertas, 1993; Tänzer, Buchwald and Stephan, 2015).

Table 1. Chemical composition and Particle size of the raw materials

Chemical composition (%)	OPC	GBFS	FA
SiO_2	19,13	31,99	28,53
Al_2O_3	4,42	14,54	19,18
Fe_2O_3	4,32	1,12	8,80
CaO	57,70	46,87	6,68
MgO	1,60	1,05	2,24
SO_3	2,32	0,82	–
Loss on Ignition, LOI	9,78	1,80	20,67
Physical characteristic:			
Average Particle Size (μm)	16,07	7,53	18,00

Source: Authors

The XRD diffractograms of the materials used in this research (OPC, GBFS, and FA) are presented in Figure 1. Regarding the OPC, crystalline phases proper to this kind of cement were found: tricalcium silicate (C_3S), tricalcium aluminate (C_3A), dicalcium silicate (C_2S), and gypsum (Y). As for the blast furnace slag, crystalline phases were observed such as calcite (C), quartz (Q), and gehlenite (G), as well as an amorphous halo between 22-36° 2μ. Fly ash reported the presence of Q, Mullite (M), hematite (H), anhydrite (A), and analcime (An), without any evidence of an amorphous phase.

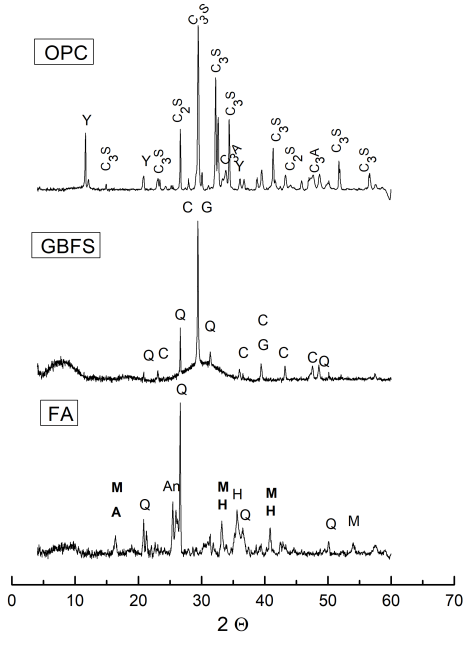

Figure 1. Mineralogical composition of the raw materials based on X-ray diffraction (XRD). Q: quartz, M: mullite, H: hematite, A: anhydrite, An: analcime, C3 S: tricalcium silicate, C3 A: tricalcium aluminate, C2 S: dicalcium silicate, Y: gypsum, C: calcite, and G: gehlenite.
Source: Authors

Design and preparation of concretes

Four types of concrete were manufactured, two as reference, OPC (100%) and GBFS blended concretes (GBFS/OPC* - 80/20); and two alkali-activated concretes (GBFS/OPC 80/20 and FA/GBFS 80/20). The activator used was a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3: SiO_2 = 32,09%, Na_2O = 11,92%, H_2O = 55,99%). The activating solution used in GBFS/OPC concrete featured a solution module (Ms = SiO_2/Na_2O) of 1 and was incorporated in a proportion of 5% of Na_2O according to slag content. In the case of the binary system (FA/GBFS), the components of the mixture were dosed to obtain molar ratios of Si/Al: 3,85 and Na/Si: 0,25. In this mix, the activator moduli Ms was 1,55. The proportions used in FA/GBFS were determined in previous studies (Valencia-Saavedra, Mejia de Gutiérrez and Gordillo, 2018). To prepare the concretes, river sand with a fineness modulus of 3,16 and crushed gravel with a maximum particle size of 12,7 mm were used according to ASTM C39 standards (ASTM International, 2018). The mix design was carried out according to the recommendations of ACI 211 Committee (2009).

Table 2 shows the proportions of the materials for each of the produced concretes. The selected slump was between 50 and 180 mm, in order to maintain medium consistency (plastic) for the manufactured concrete, which is ideal for handmade placements and reinforced sections. Then, the concrete specimens were kept for the first 24 hours in metallic molds under relative humidity (>90%), at room temperature (24 °C), and covered with wet foams. Subsequently, the alkali-activated concrete specimens were removed from the molds and cured in a wet chamber (90% R.H. and 24 °C) up to the test ages. OPC and GBFS/OPC* 80/20 samples were submerged and cured in water (100% R.H.).

Experimental tests

The compressive strength test was carried out on cylindrical samples (76,2 mm diameter x 152,4 mm height) as specified by ASTM C109 (ASTM International, 2016). The measurements of compressive strength were conducted at 7, 28, 180, and 360 days of curing, using three (3) samples for each mixture and test age.

Table 2. Design of mixtures and properties in the fresh state of the concretes

Component proportions, kg/m^3	Concrete Mixes			
	OPC	GBFS/OPC*	GBFS/OPC	FA/GBFS
Cement	400	80	80	–
FA	–	–	–	320
GBFS	–	320	320	80
SS	–	–	44,6	158,4
NaOH	–	–	12,2	28,6
Fine aggregate	972,7	989,9	989,9	972,7
Coarse Aggregate	704,4	716,9	716,9	704,4
L/S ratio	0,48	0,48	0,48	0,48
Slump (mm)	60	50	70	180

Source: Authors

To measure the water absorption capacity of each mixture (capillary sorption), two cylindrical samples (76,2 mm diameter and 76,2 mm height) were used per evaluated mixture, according to the Swiss Standard SIA 162/1 (EMPA, 1989). After 28 days of curing, the samples were dried in a

furnace at 60 °C for 48 hours until a constant weight achieved. Then, the lateral surface of each cylinder was covered with waterproof paint. The samples were placed on a tray in a sealed container, in such a way that the lower surface was in contact with the water up to a height of 5 mm, allowing the water to enter through it. At different times, the samples were removed from the container and weighed to evaluate the weight gain. The kinetics of water absorption in concrete can be described approximately by the coefficients: *Water absorption coefficient* $-K$ ($Kg/m^2s^{1/2}$) and *Resistance to water penetration* $-m$ (s/m^2). K corresponds to the initial slope of the sorptivity plot (water absorption expressed as Kg/m^2 versus the square root of time in $s^{1/2}$). The value of "m" is calculated using Equation (1):

$$m = t/Z^2 \quad (1)$$

where t is the saturation time of the sample, and Z is the height of the evaluated sample.

The concrete's resistance to chloride ion penetration was evaluated by determining the charge passed through the concrete, as specified by ASTM C1202 (ASTM International, 2019a). After 28 days of curing, two 50-mm-long disks were cut from the middle segment of the manufactured cylinders. Specimens with diameters of 76,2 mm were used. The samples were conditioned according to the procedure mentioned in the standard and then placed in the test cell. One side was in contact with a 3,5% NaCl solution, and the other one, with a saturated solution of calcium hydroxide ($Ca(OH)_2$). Direct current (DC) at 60 V was applied, and the current flow was recorded in 5-minute intervals to cover a period of 6 hours. It is noted that this methodology is used to evaluate chloride permeability in concretes based on OPC; there is no standard method for alkali-activated materials.

In addition, the resulting hydration products were characterized using X-ray diffraction techniques on a PanAnalytical X'Pert MRD diffractometer with Cu Ka radiation and a step size of 0,020° in a range between 5 and 60° 2θ. Microstructural characterisation was conducted by scanning electron microscopy (SEM) using a JEOL JSM-6490LV high-vacuum device (3 x 10^{-6} Torr) at an acceleration voltage of 20 keV.

Results and discussion

Compressive strength

Figure 2 shows the average compressive strength values with respect to the curing age of the different concretes that were evaluated in this study, namely, reference concretes (non-activated binders) (OPC and GBFS/OPC*) and alkali-activated concretes, GBFS/OPC-AA and FA/GBFS-AA.

As expected, gain in mechanical compressive strength from 7 to 360 days of curing is observed for all the evaluated mixtures (Figure 2). The strength gains of the AA concretes between 7 and 28 days of curing were 30,17% for GBFS/OPC, and 23,51% for FA/GBFS. The alkali-activated concretes GBFS/OPC 80/20-AA and FA/GBFS-AA exhibited a similar strength gain (43%) between 28 and 360 days of curing. It should be noted

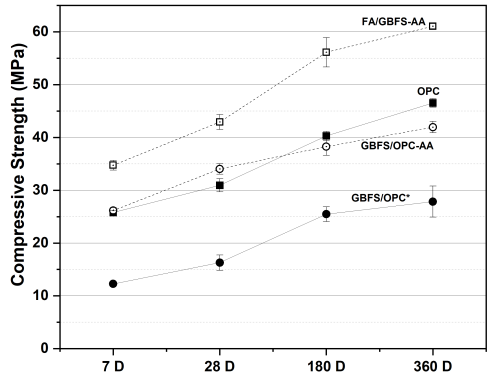

Figure 2. Compressive strength of the OPC and alkaline activated (GBFS/OPC and FA/GBFS) concretes.
Source: Authors

that the FA/GBFS alkali-activated concrete presented the best compressive strength: 43 and 61 MPa at 28 and 360 days of curing, respectively. This behaviour of the FA/GBFS 80/20 concrete, which was not appreciable in samples with 100% FA (Valencia-Saavedra, Mejia de Gutiérrez and Gordillo, 2018), can be attributed to the presence of the blast furnace slag, a material that provides calcium to the system, generating hydrated calcium silicate gel as reaction product, in addition to the aluminosilicate gels proper to the alkaline activation of fly ash (C-A-S-H/N-A-S-H). This performance agrees with those reported by other authors (Manjunatha et al., 2014; Gopalakrishnan and Chinnaraju, 2019; Nath and Kumar, 2014). At 7 and 28 days for FA/GBFS concretes (80/20) designed with 400 kg/m^3 of precursor, Nath and Kumar (2014) reported compressive strength values similar to those obtained in the present study, although the proportions of activator and the characteristics of fly ash were different. On the contrary, Chi (2016) reported a compressive strength lower than 20 MPa at 28 days using a FA/GBFS ratio of 75/25 concrete specimens. The addition of GBFS as a partial replacement of fly ash contributes to the material hardening at room temperature and to develop greater strength at early and longer ages. Additionally, the presence of the two gels (C-A-S-H and N-A-S- H) produces a significantly more compact microstructure than the one generated by OPC cement paste (Chotetanorm, Chindaprasirt, Sata, Rukzon and Sathonsaowaphak, 2013; Deb, Nath and Sarker, 2014; Marjanović, Komljenović, Baščarević, Nikolić and Petrović, 2015; Ryu, Lee, Koh and Chung, 2013, Ismail et al., 2014). In conclusion, the coexistence and interaction between N-A-S-H and C-A-S-H gels generate a higher degree of cross-linking within the reaction products.

The blended GBFS/OPC* 80/20, compared to OPC concrete, displays a significantly reduced compressive strength, especially at early ages: 12 MPa at 7 days. The early performance of the GGBS/OPC binder is poor because the hydration of GGBS needs the presence of calcium hydroxide ($Ca(OH)_2$), which is formed through the hydration of OPC (Angulo-Ramírez, D. E., Mejía de Gutiérrez, R., and Puertas, F., 2017). On the contrary, when this material is alkali-activated (GBFS/OPC-AA), its resistance increases up to 110% at 7 days

of curing. At greater ages (180, 360 days), the increase was up to 50%. The mechanical development of GBFS/OPC-AA was comparable to that reported by OPC concrete. Amer, Kohail, El-Feky, Rashad, and Khalaf (2020), using the Taguchi method, reported that the optimum GBFS/OPC ratio and solution modulus (Ms) were 80/20 and 1,0, coinciding with the proportions used in this study. However, the authors used Na_2O = 10%, which is two times higher than what was used in this study (5%). The performance of an alkali-activated GGBS/OPC binder with GGBS content of 70 to 100 wt%, cured at temperatures of 20, −5, and −20 °C, was studied by Zhang, Yang, Ju, and Yang (2020). The highest compressive strength was achieved when the GGBS content was 80 wt% (62,7 MPa in 28 days at −5 °C). The authors suggest that this type of binder can be an environment-friendly cementitious material for winter construction. These recent results show an opportunity to use these materials at low temperature conditions, where the hydration processes of conventional cements can be slow.

Microstructural analyses of activated alkali systems performed by X-ray diffraction and electron microscopy (SEM) confirmed the presence of C-A-S-H/N-A-S-H gels and the densification of the generated microstructures. The X-ray diffractograms, after 28 days of normal curing of the FA/GBFS and GBFS/OPC systems are presented in Figure 3. The presence of the crystalline phases associated with the original materials, which were not affected by the alkaline solutions, was observed (Mejía, Rodríguez, and Mejía de Gutiérrez, 2014). Hydration products such as gehlenite, hydrotalcite, and a crystalline portion of C-S-H gel were identified in the GBFS/OPC system, the latter of which was also found in the diffractogram of the FA/GBFS system. For both systems, the peak located at approximately 30° 2θ is attributable to the main phase C-(A)-S-H, which overlaps with that of calcite. A crystalline phase of sodium aluminosilicates (analcime, $NaAlSi_2O_6H_2O$) was also identified, thus confirming the presence of a NASH-type binding gel in the FA/GBFS system.

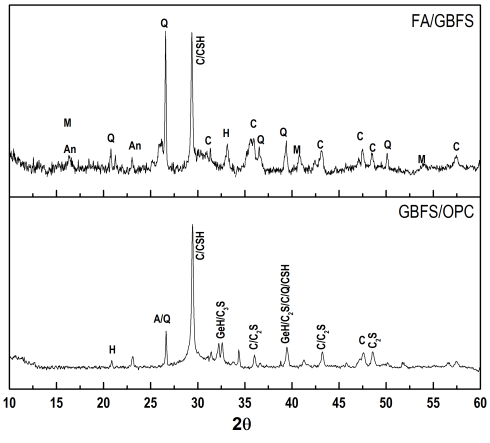

Figure 3. X-ray diffractograms of the FA/GBFS and GBFS/OPC-AA systems. A: Aragonite; C: Calcite; H: Hydrotalcite; GeH: Hydrated gehlenite (C_2ASH_8/C_4AH_{13}); Y: Gypsum; Q: Quartz; M: Mullite; An: Analcime; H: Hematite.
Source: Authors

Figure 4 shows the microstructures observed by SEM for the tested concretes. A good paste-aggregate adhesion can be seen in the activated materials, in addition to a highly dense microstructure, which is related to the favorable mechanical properties that were obtained. This feature is also related to the increased tortuosity within the structures of these systems, which contributes to their greater resistance to the penetration of water and aggressive agents such as chloride ions seen in the evaluation of physical properties.

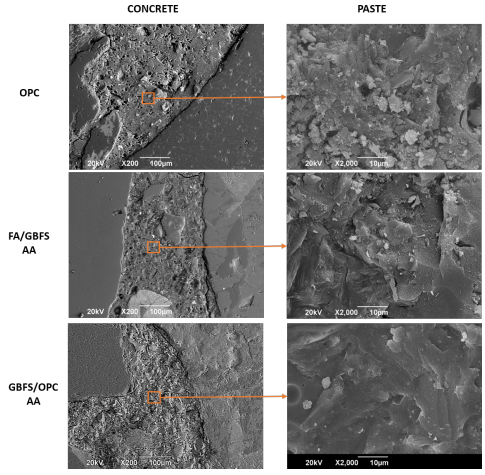

Figure 4. Microstructure of the FA/GBFS and GBFS/OPC alkali-activated concrete (left) and paste (right) systems observed by scanning electron microscopy.
Source: Authors

Physical properties

Table 3 shows the results of the water absorption test based on capillary action for the concretes, which were evaluated after 28 days of curing, where "k" represents the absorption coefficient and 'm' the resistance to water penetration. The results show that the alkali-activated concretes GBFS/OPC and FA/GBFS, featured lower absorption coefficients (52% and 10%, respectively) compared to 100% OPC. These concretes also exhibited a greater resistance to water penetration, with values of 33% and 71%, respectively, compared to conventional OPC.

Table 3. Capillary absorption properties of concretes (*without alkali-activation)

CONCRETE MIX	OPC	GBFS/OPC*	GBFS/OPC	FA/GBFS
k (kg/m^2.seg$^{1/2}$)	0,0292	0,0190	0,0140	0,0262
m*10^7 (s/m^2)	1,89	2,51	2,51	3,24

Source: Authors

Wardhono, Gunasekara, Law and Setunge (2017) found significant differences between the water permeated by concretes based on FA and GBFS. However, in the case of FA/GBFS compared to the 100% OPC, the reduction is attributed to the sodium aluminosilicate gels that are generated during the geopolymerisation process. This gel fills the spaces and interfaces formed between the paste

and aggregates, thereby reducing the porous structure, and generating a denser microstructure, as previously evinced. The greater resistance to water penetration presented by the alkali-activated concretes indicates the refinement of pores and an increase in the tortuosity of the pore network in this system. In general, the coexistence of C-A-S-H and N-A-S-H gels in FA/GBFS concrete explains the positive behavior of this material. The best characteristics presented by GBFS/OPC and FA/GBFS are related to the greater densification and compactness observed in the SEM test, and due to the lower number of capillaries or permeable pores present in this type of alkaline-activated materials (Valencia-Saavedra et al., 2018; Chotetanorm et al., 2013; Qureshi and Ghosh, 2014; Aydin and Baradan, 2014).

Figure 5 shows the results of the rapid chloride permeability test, performed on OPC, GBFS/OPC, and FA/GBFS concretes after 28 days of curing, based on the procedure described in ASTM C1202 (ASTM International, 2019a). From the results obtained in this study, it can be deduced that the chloride resistance in the evaluated AA concretes is higher than in OPC. According to the criteria defined in the ASTM standard, the penetrability of the chloride ion in OPC can be classified as moderate, unlike the concretes with alkaline activation, which showed low penetrability in the case of FA/GBFS and very low penetrability for GBFS/OPC. This finding agrees with the studies of Bernal, Mejía de Gutiérrez and Provis (2012) and Bernal, De Gutierrez, Delvasto, and Rodriguez (2010) who investigated 100% blast furnace slag alkaline-activated concretes and reported filtered load values below 1600 Coulomb. Likewise, Ismail et al. (2013) indicated a better behavior of the slag/fly ash concrete of alkaline activation and concluded that, in the presence of chlorides, these concretes feature lower chloride ion penetration and higher amounts of bound chlorides when compared with conventional OPC concrete. Yang, Yao and Zhang (2014) attributed this positive behavior of the FA/GBFS concrete to the incorporation of blast furnace slag as a precursor material, which contributes to the pore refinement within the structure, thus reducing the sorptivity and restricting the penetration of chloride ions, as was verified in the present study.

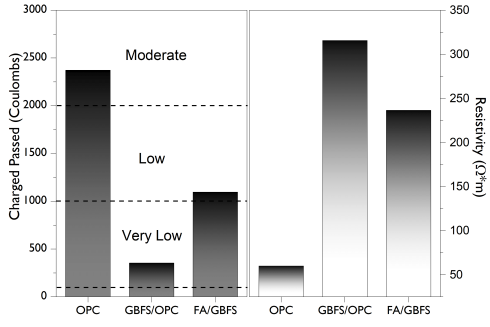

Figure 5. Rapid chloride permeability test of OPC and alkali-activated concretes FA/GBFS and GBFS/OPC: a) charge passed (Coulomb) b) resistivity of the concrete (Ω*m).
Source: Authors

Regarding the resistivity values calculated from the initial current results in this test, it was possible to notice increases in the alkaline-activated concretes of up to 5 times the value reported by OPC (Figure 5). The current results could be indicative of the concrete porosity. However, the connectivity, and tortuosity of the pore network and electric properties of concrete affected the results of this test. Therefore, the electrical conductivity of concrete depends on the pore solution, and the AA concretes present a high ionic concentration because of the presence of mobile cations such as Na+. For this reason, it is only possible to compare concretes with a similar pore solution chemistry (FA/GBFS and GBFS/OPC, both alkali-activated concretes) (Ismail et al., 2013). The highest electrical conductivity presented by the alkaline activated FA/GBFS, compared to the GBFS/OPC, could be attributed to the potentially high conductivity of the pore solution generated in this material, due to the high concentration of Na+ and OH- ions, present as a consequence of higher content of sodium silicate and sodium hydroxide in the mix (see Table 2) (Chi, 2012; Lloyd, Provis and van Deventer, 2010; Ravikumar and Neithalath, 2013). However, according to ASTM C1202, the results obtained of charge passed and resistivity of alkali-activated materials evaluated in the present study were consistent with each other (Figure 5).

It is important to note that this standard is specific for OPC-based materials and not for alkaline-activated materials, for which international standards have not yet been defined. This test has been controversial for the reasons described above, and therefore it urges the development of specific protocols for alkali-activated concretes (Ismail et al., 2013; Arbi Ghanmi, Nedeljković, Zuo and Ye, 2016). On the other hand, Thomas, Ariyachandra, Lezama and Peethamparan, 2018) studied different chloride permeability methods for AA concretes. They found that RCPT (ASTM C1202) results correlated very well with diffusion coefficients from salt ponding tests according ASTM C1543 (ASTM International, 2010), unlike resistivity measurements with these results.

Conclusions

The results obtained in the present research led to the following conclusions:

The alkaline-activated FA/GBFS 80/20 has a better mechanical performance based on compression testing at ages up to 360 days of curing, in comparison with conventional 100% OPC concrete. The compressive strengths of FA/GBFS concrete were 34,75 MPa and 61,07 MPa at 7 and 360 days of curing, respectively, which are significant findings, considering the low-quality of the FA used. The alkali-activated blended concrete GBFS/OPC 80/20 presents a similar compressive strength to OPC: 26,15 MPa and 42 MPa at 7 and 360 days, respectively.

The alkali-activated concretes GBFS/OPC and FA/GBFS feature greater resistance to water penetration, 33 and 71% higher than those obtained in OPC. According to the results of permeability to the chloride ion, evaluated using the standard ASTM C1202 (ASTM International, 2019a), concretes FA/GBFS 80/20 and GBFS/OPC 80/20 could be

considered to have a low and very low permeablility, respectively.

Therefore, it is concluded that these two types of alkaline-activated concretes (FA/GBFS 80/20 and GBFS/OPC 80/20) have characteristics that are suitable for various applications in the construction sector, making them good alternative materials to Portland cement concrete.

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Soft Skills in Engineers, a Relevant Field of Research: Exploring and Assessing Skills in Italian Engineering Students

Habilidades transversales en ingeniería, un ámbito de investigación relevante: Explorando y evaluando habilidades en estudiantes de ingeniería italianos

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ABSTRACT

Soft skills are important for any career and are necessary to access and face the labor market. This research focuses on soft skills by exploring engineer profiles. It also determines how soft skills are developed through the study of a representative sample of 314 undergraduate engineering students from 15 different Italian universities. The instrument used is a questionnaire that investigates soft skills and is based on the Business-focused Inventory of Personality (BIP). Answers are grouped into four areas: intrapersonal, interpersonal, activity development, and impression management. Results show that these engineers have more self-confidence than the reference sample; they demonstrated a great commitment in setting job goals and pursuing projects, a good emotional adaptation to social situations, and enough attitudes in terms of problem solving and openness to change. Perception on the ability to work under pressure is in the average, and they seem ready to take on challenging tasks. The score shows that engineers from the sample are able to express positive and negative ideas and feelings in balance with the reference average, but sometimes they have difficulties in establishing personal relationships. Therefore, they are unable to understand the moods of those who around them and may also have difficulty in understanding their expectations. This results in some difficulties in teamwork. The general result underlines the opportunity of empowerment programs regarding soft skills.

Keywords: soft skills, engineer, BIP, curriculum, university

RESUMEN

Las habilidades transversales son importantes para cualquier carrera y son necesarias para acceder y afrontar el mercado laboral. Esta investigación se enfoca en el tema de las habilidades transversales explorando los perfiles de los ingenieros. También determina cómo se desarrollan las habilidades sociales a través del estudio de una muestra representativa de 314 estudiantes de ingeniería de 15 universidades italianas diferentes. El instrumento utilizado es un cuestionario que investiga las habilidades interpersonales basado en el Business-focused Inventory of Personality (BIP). Las respuestas se agrupan en cuatro áreas: intrapersonal, interpersonal, desarrollo de la actividad y gestión de la impresión. Los resultados muestran que estos ingenieros tienen más confianza en sí mismos que la muestra de referencia; demostraron un gran compromiso en establecer metas laborales y seguir proyectos, una buena adaptación emocional a las situaciones sociales y actitudes suficientes en términos de solución de problemas y apertura al cambio. La percepción sobre la capacidad de trabajar bajo presión se encuentra en el promedio, y ellos parecen dispuestos a asumir tareas desafiantes. El puntaje muestra que los ingenieros de la muestra son capaces de expresar ideas y sentimientos positivos y negativos en equilibrio con el promedio de referencia, pero a veces tienen dificultades para establecer relaciones personales. Como resultado, no pueden comprender los estados de ánimo de quienes los rodean y pueden tener dificultades para comprender sus expectativas. Esto resulta en algunas dificultades para el trabajo en equipo. El resultado general subraya la oportunidad de un programa de empoderamiento en habilidades transversales.

Palabras clave: habilidades transversales, ingeniería, BIP, currículum, universidad

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Introduction

Currently, soft skills are receiving attention from different age groups alongside occupational education programs to better equip people for their future careers. Nevertheless, introducing such concepts in a fitting way is an important challenge in higher education. There are a lot of definitions regarding soft skills. In general, education programs focused on soft skills have the goal to make or reduce the number of unemployed graduates and to efficiently match graduates with companies, not only in technical matters, but also in the aspects related to company values. According to "The Research Agenda for the New Discipline of Engineering Education" (Borrego and Bernhard, 2011) the skills that future engineers must master in the classroom and develop during their professional practice are mainly soft skills. These are transferable behaviors that can be used in different contexts of life, specifically in highly competitive work scenarios (Schleutker, Caggiano, Coluzzi and Poza-Lujan, 2019). They are absolutely necessary to access the labor market, and they have become more crucial to acquire in engineering professional contexts, together with hard and technical skills (King, 2012; Gemar, Negrón-González, Lozano-Piedrahita, Guzmán-Parra and Rosado, 2019). Today's engineering graduates have a plenty of technical knowledge, but mostly lack the social skills required by current job settings, such as leadership, communication and teamwork. One of the crucial areas of research in engineering education is focused on designing higher education engineering courses to predispose competent, autonomous, and decision-making future engineers (Itani and Srour, 2016) in order to respond to labor market demands for highly qualified professionals. Engineering has focused mainly on its technical aspects. This is because engineering is more isolated from human relations than other disciplines. In these disciplines, the result is the most important thing, and focusing on personal matters is not necessary to obtain successful results (Barrera, Duarte, Sarmiento and Soto, 2015). However, currently, the classical vision of an engineer working alone, designing some personalized product, has changed. Companies develop a lot of projects with a lot of people involved. That means that relations between different people in a project are one of the pillars to achieve its goals (Brunhaver, Korte, Barley and Sheppard, 2017). Therefore, some personal characteristics, which we prefer to call soft skills, such as teamwork or leadership, have started to be recognized. Traditionally, these skills are not considered in the curriculum of engineering programs. However, these soft skills needs are being considered, especially since engineers perform their work in a project-oriented environment (Henkel, Marion and Bourdeau, 2019; Ballesteros-Sánchez, Ortiz-Marcos, Rodríguez-Rivero and Juan-Ruiz, 2017). In emerging fields of engineering, such as Information and Communication Technologies (ICT), the study of soft skills is one of the future trends (Matturro, Raschetti and Fontán, 2019).

These aspects raise some interesting questions: what soft skills are necessary in engineering? Can soft skills be learned? To answer these questions, it is necessary to know the current state of soft skills in engineering, in other words, what are the most common soft skills in engineers, and if these soft skills depend on age or gender. The research presented in this paper is focused on determining the most relevant soft skills that engineers have in order to answer these questions, as well as whether there are differences between the soft skills that engineers possess and the average of other university students. If there are, probably the syllabus of the degrees and masters engineering curriculum must consider incorporating them as part of their training. It is important to know these soft skills since they are are necessary to design university programs based on competencies (Tulgan, 2015).

Defining soft skills

There is a significant parallelism between system components: hardware (hard skills) and software (soft skills). Without hardware, software does not work, and without software, hardware cannot be used efficiently. From a business point of view, engineers need soft skills to obtain benefits from their hard skills (Robles, 2012). Previous researchers noted that many graduated engineers have good technical skills (or hard skills) but not enough soft skills. That is, there is an insufficiency of skills related to employability and moral values, communication and leadership, confidence level, and ability to adapt in the workplace (Beckton, 2009; Elsen, Jaginowski anf Kleinert, 2005; Leroux and Lafleur, 2006; McIntosh, 2008).

Empirical researches confirm that, nowadays, employers are hunting for workers who have good technical skills but have additional skills such as communication, interpersonal, teamwork, problem-solving, thinking, and technology skills, as well as continuous learning and a positive work ethic (Raybould and Sheedy, 2005). Soft skills, as generic skills, have become a main factor that is needed by employers, and graduates must consider this to start any career (Hinchliffe and Jolly, 2011; McQuick and Lindsay, 2005). This was demonstrated when many unemployed graduates stated that they needed additional training programs to improve soft skills as well as lifelong learning skills, team building, career development, interpersonal skills, and the especially necessary entrepreneurial skills (Fabregá, Alarcon and Galiana, 2016; Pineteh, 2012).

Soft skills are among the skills that are necessary to improve the performance of self-employment graduates in relation to international needs. The increase in the total number of unemployed graduates is one of the subjects that arises, due to the lack of proficienct soft skills (Redomero, Caggiano, Poza-Luján, and Piccione, 2019). For this reason, it is necessary to deepen and develop this subject.

European university curriculum

Currently, continuous change in the socioeconomic environment demands highly skilled graduates from universities (Possa, 2006; Sleezer, Gularte, Waldner and Cook, 2004; Weil, 1999). Consequently, it is necessary to match companies' skills needs with the skills provided by universities in order to increase the quality of the alumni

(Elias and Purcell, 2004; Teichler, 2003). Following the Bologna Declaration on June 19, 1999, titled *The European Higher Education Area*, and given their importance in the development of a knowledge-based economy, European universities are required to produce graduates who are able to respond to the ever-changing workplace requirements (Andrews and Higson, 2008). This has resulted in questions about the ability of graduates to meet the needs of employers (Caggiano, Schleutker, Petrone and González-Bernal, 2020). Certainly, "serious concerns have been expressed about an increasingly wide 'gap"' between the skills that graduates have and the requirements of the global work environment (Andrews and Higson, 2009, p.1; Mocanu, Zamfir, and Pirciog, 2014).

Curriculum development is a key educational process that can support the innovative capacity of a higher education institution. Thus, implementation of educational curricula in the European universities should always be up to date to make certain that graduates possess not only knowledge but also mastery of soft skills (Stevenson and Bell, 2009). Communication skills, life-long learning, entrepreneurship skills, and moral and professional ethics are some of the skills needed by graduates to improve their employability (Evans, 2006; Pineteh, 2012). There are growing concerns for graduate employability and the expansion in the size and diversity of student populations (Fallows and Steven, 2000).

In the case of engineering students, the importance of soft skills has been acknowledged in recent years (Bancino and Zevalkink, 2007). Recent studies indicate the complexity of the learning process to determine which soft skills are necessary for engineers (Aponte, Agi, and Jordan, 2017). Consequently, it is very important to incorporate soft skills to the curriculum, especially in order to obtain the degree certifications of the international agencies. In this case, such skills are called 'professional skills' (Shuman, Besterfield-Sacre, and McGourty, 2005).

The concept of competency-based curricula appears in order to incorporate competencies into the engineering curriculum (Lunev, Petrova, and Zaripova, 2013). This model focuses on the learning process and is oriented towards results (Tomić et al., 2019). This makes the model perfect for engineering degrees. Given that soft skills are important in engineering and that the competency-based model is very suitable for these disciplines, it is convenient to determine which soft skills engineers must have and develop. These competences must be acquired by students but are also necessary in teachers (Carvalho, Corrêa, Carvalho, Vieira, Stankowitz, and Kolotelo, 2018).

It is also convenient to quantize the dependence on soft skills with regarding some structural aspects. Among the various aspects, it is possible to highlight two statistical dimensions: age and gender. In the case of soft skills, age can be used as a variable (Fournier and Ineson, 2014). However, experience is not age, and it is a more accurate factor in acquiring certain soft skills (Joseph, Ang, Chang, and Slaughter, 2010). Usually, students do not have enough labor experience to deem this variable significant. In the case of this study, we consider age because the people who answered the questionnaire were mainly last year students who became graduates during this study.

The perception of the need for soft skills in engineering varies depending on the experience (Chanduví, Martín, and De los Ríos, 2013). That is to say, when an engineer has been working for many years, he or she knows what hard skills are necessary, but experience also allows to determine which ones must be developed. This is due to the fact that experience provides knowledge about the personal profiles that drive engineering projects to have a good result. Regarding gender, it is obvious that engineering has an issue to solve (Wang and Degol, 2017). It would be very important to know if the appreciation of transversal competences is different in terms of gender, since it could determine whether the low percentage of women in engineering depends on hard skills or soft skills. Knowing what competencies are different between men and women would make it possible to improve the actions aimed at achieving more gender equality in engineering.

Method and tools

This research was classified as descriptive, since the general objective was to determine the skills already developed by graduates in engineering, in order to address the lack according to the needs of the job market. In this sense, we tried to identify and characterize a series of soft skills, highlighting their qualities and characteristics. It was a non-experimental, cross-sectional design that simultaneously collected data, particularly during the months of April 2015 to June 2018. The research focused on a population of undergraduates in different engineering disciplines in Italy. Out of this population, an accidental sample was developed through the Department of Engineering of the University of Roma Tre, through personal contacts with a snowball sampling, and thanks to the publication of the questionnaire in different social networks.

The final sample used consisted of 314 people. Although it is a small sample, it must be considered that more than 1 000 responses were received. However, only those persons who were students and graduated within two years after taking the survey were considered. This is because we wanted to determine the soft skills of the graduates, but we also desired to know the needs of the students, in order to adapt them to the curriculum. The result was a small but qualified sample.

Likewise, the confidentiality of personal data was guaranteed, requesting permission to treat them according to the Italian law D'Lgs 196 of June 30, 2003. The next step in this research was to collect data from Spanish informatics engineering graduates. With this comparison, we proposed to extend the study into two branches -European and South American undergraduates and/or graduates- in order to compare the cultural and economic influence in the development of soft skills.

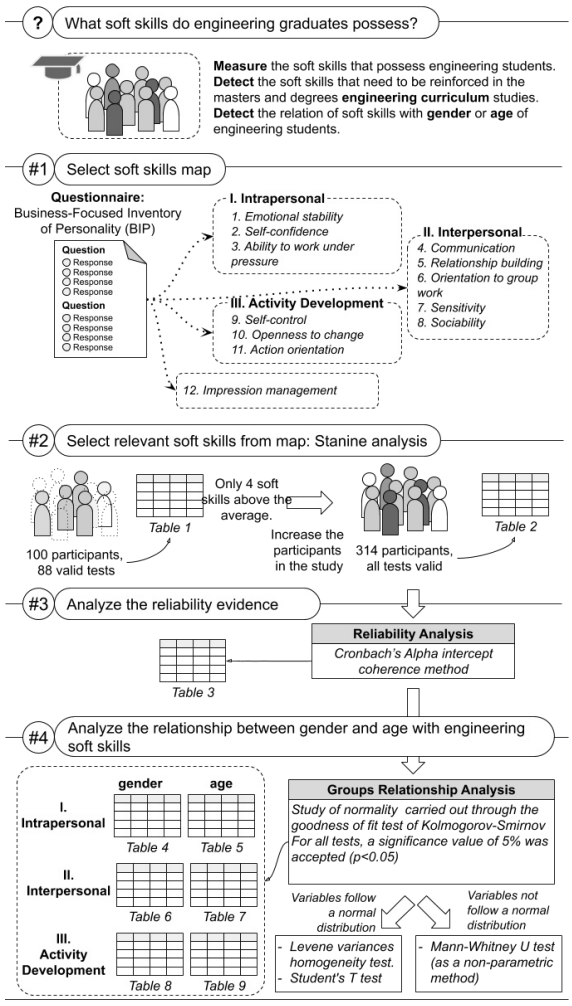

Figure 1. Full process of experimentation carried out and presented along with the performed.
Source: Authors

Sample

A representative sample of 314 engineering undergraduates from 15 universities of Italy s selected. Among all respondents, there were 221 (70,38%) male students and 93 female students (29,62%), all aged between 19 and 24, with the exception of a 52-year-old subject. To avoid altering the presented age-related study, we had separate the main group and the exception in another one. Results only considered 19 to 24 because one exception could cause a high bias in the analysis. 49,68% of them were bachelor students (three-year engineering program) and 50,32% were master's degree students (three-year engineering program). Regarding the type of engineering, students came from Computing and Systems Engineering (70,06%), Industrial Engineering (28,66%), and the remaining percentage (1,7%) was divided between different engineering branches: mechanical, civil, environmental, electronic, management, transportation, energy, and biomedical engineering.

Procedure

Participant consent was obtained before undertaking the study. The students volunteered and indicated their agreement to participate in the study through a form.

They were informed that their participation was completely voluntary and that all collected information would be anonymous and confidential. The questionnaires were administered in the last year of their degree to test the above-mentioned hypothesis: whether soft skills were developed in their academic paths.

Instrument

Detecting soft skills like creativity requires the use interesting methods and specific tools (Olivares-Rodríguez, Guenaga, and Garaizar, 2017). Questionnaires are the most frequent, since they allow homogenizing results and are easily filled out by students. The latter justifies their use in the studied population (Fernández-Sanz, Villalba, Medina, and Misra, 2017). Questionnaires are easily included in methods. For example Redoli, Mompó, De la Mata, and Doctor (2013) present a full procedure to detect and train soft skills which uses questionnaires in the early stages of the training. On the other hand, to measure a concrete soft skill, concrete methods can be used. For example, Joseph, Ang, Chang, and Slaughter (2010) use the critical incidents methodology to measure practical intelligence. A list of different methodological approaches for measuring soft skills can be found in Balcar (2014). The greater is the number of evaluated soft skills, the more generic should the employed method be. That is why we decided to use a questionnaire as a measuring tool instead of other practical methods.

The questionnaire included the following sections: Sociodemographic characteristics (gender, age and, provenance) and studies (university and engineering type). The next section was the Business-focused Inventory of Personality (BIP). Engineers develop their activities mainly in companies, so the use of BIP is justified by the similarities between the evaluated competences and the meta-competencies that are usually required in engineering (Chanduví et al., 2013). Additionally, the questionnaire has been adapted and translated for the Italian population by Luissa Fossati and Matteo Ciancaleoni (2013).

Regarding BIP, to avoid equidistant position, a specific used response format was chosen. The answers were arranged into a six-point scale that varies between 'completely true' and 'completely false', between which four intermediate points are not anchored. These questions are based on dichotomous statements, so the respondent must choose between one or the other pole. For example, 'I prefer to answer emails than to make phone calls' can be answered in the range of 1 ('completely false for me') to 6 ('completely true for me'). In this case, the number of responses is even to avoid the 'impartial' effect; it is necessary to decide in one way or another.

The current version of the BIP is the result of an intense revision (Fossati and Ciancaleoni, 2013). Not all the variables in the questionnaire have been selected, in order to cover

only the competences closest to the engineering field of work (Allen, Reed-Rhoads, Terry, Murphy, and Stone, 2008). The evaluated scales are grouped into three areas plus one isolated Impression Management skill. Next, we present the definition of these soft skills which were used and explained to participants.

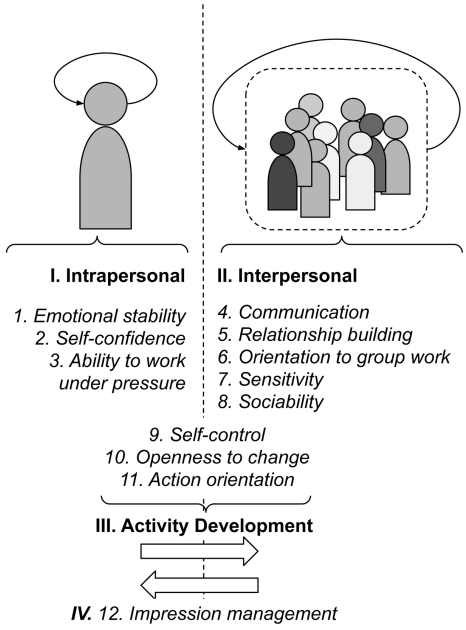

Figure 2. Areas in which the BIP questionnaire separates the soft skills and their placement in the process of personal interactions.
Source: Authors

Intrapersonal area

- **Emotional stability**: It focuses on appropriate management of emotional reactions. It concerns the ability to react positively to stressful or difficult situations in life.
- **Self-confidence:** It is the conviction or security of being capable of doing a good job. When there is no self-confidence, other personal skills can be ignored.
- **The ability to work under pressure**: It gives us the image that the sample have of themselves regarding the ability to perform their functions in adverse circumstances while maintaining a constant level of efficiency.

Interpersonal area

- **Communication**: It is assessed through assertiveness, a social ability that allows us to express our rights, opinions, ideas, needs, and feelings in a conscious, clear, honest, and sincere way without harming others. It includes the ability to convince others, persevering in supporting one's position.
- **Relationship building**: It is close to the Big Five Model extroversion construct (McRae and Costa, 1987), but there are differences with the present research. In this case, it concerns the development of interpersonal relationships and the creation of a network of contacts.
- **Orientation to group work**: The preference to work in a group or individually is evaluated, as well as the ability to integrate into work groups and the level of performance in both contexts.
- **Sensitivity**: It is the ability to interpret and understand people's thoughts, conduct, feelings, and concerns; to perceive if any behavior is appropriate depending on the social situation.
- **Sociability**: This has similarities with the broad domain of the Big Five Model's Agreeableness (McRae and Costa, 1987). It concerns the ability to interact friendly and kindly. It deals with a basic social competence in the processes of adaptability to new environments or new conditions of social coexistence.

Activity development area

- **Self-control**: It is inserted in the Conscientiousness factor from the Big Five Model (McCrae and Costa, 1985). However, in the present case, we mean the commitment with work objectives or projects. This dimension is also based on planning, organization, and execution of tasks.
- **Openness to Change**: This scale shows an overlap with the openness to the experience construct of the Big Five Model (McCrae and Costa, 1985). Still, this factor has a greater breadth in the model. In the present research, adaptability and flexibility are evaluated. It concerns adaptation while coping with changing situations.
- **Action Orientation**: It broadly corresponds to the construct described by Kuhl and Beckmann (1994). It is a bipolar dimension, aimed at evaluating the orientation to the action in opposition to the orientation to the state. The first one favors the transformation of intention into action, while the other is characterized by having thoughts related to the attainment of a goal in the mind.

Impression Management

It comprises the tendency for responses to be socially desirable. This variable refers to the own impression about the effect of the social interaction and has a direct relation with important aspects such as motivation and ethical point of view (Brockmann, Clarke, Méhaut, and Winch, 2009).

Data analysis

Data was collected through Google Forms, through a payment account for the project. This account allowed to obtain progressive copies of all the changes and guaranteed the integrity and full availability of the data. Access to data could

only be done by researchers. Given that the study did not collect private data that enabled the recognition of people, it was not allowed to alter the response of the participants. The data processing was carried out through the exporting a CSV file. A data audit was performed to verify that the analysis program had not altered the original data.

SPSS (IBM Corp., 2015) was used for all analyses. Descriptive statistics for individual item scores of the soft skills competency level were analyzed to establish a general profile of the engineering students' self-assessment qualification patterns. The BIP is a questionnaire that refers to statistical rules. In other words, it defines the level of each characteristic detected in the examined subject by comparing it to the raw score. The normative scores are expressed as stanine points on a scale that has an average of 5,5 and a standard deviation of 2. In order to compare results, we used the results from the whole study performed by authors as a reference group. These groups included students from different degrees and different Italian universities. The reference group consisted of undergraduates from different degrees: 314 from engineering, 174 from education and 683 from different sciences degrees (Chemistry, Biology, Mathematics and so on). Regarding gender, 48,3% were women and 51,7% men. The age average was 21,3 years old. The characteristics of the reference group were close to the characteristics of the applied questionnaire. The average of these groups, including other degrees, were the values used as a reference group in the soft skills level analysis. This group was used to compare the results of concrete subsets. For example, in Redomero et al. (2019), only education and engineer degrees were compared.

Then, a psychometric validation was performed for the item set. The reliability analysis of the questionnaire was carried out with the sample of engineers by using Cronbach's internal consistency method. This coefficient allows to verify that the items measured the same variable on a Likert-type scale and were highly correlated. It varies in value from 0 to 1: the higher the score, the more reliable the scale will be.

The comparison between means of different groups (age, gender) was carried out through independent samples T-test, checking first if the variances were similar through the Levene contrast test. Both Mann-Whitney U and Kolmogorov-Smirnov non-parametric tests were performed to compare two different and unpaired groups of two-variable data. These methods compute P values that test the null hypothesis that the two compared groups have the same distribution. For all tests, a significance value of 5% was accepted ($p < 0,05$).

Results

Soft skills level in engineering students

In the first phase of the research, the first deep analysis was performed on a sample of 100 subjects, but only 88 questionnaires were considered valid. The fee costs and time invested in carrying out a complete test is very high. For this reason, a first sample was chosen to determine which soft skills should be analyzed in more detail. This research was intended to verify that soft skills were below the reference group average of the questionnaire. In this case, with a representative sample of 88 subjects, with scores above the average and with the knowledge that, by shortening the test, more subjects would be reached. Table 1 shows the high scored soft skills in engineering students.

Table 1. Soft Skills with high scores obtained by engineering students

Soft Skill	N	Mean	Standard deviation
1. Emotional stability	88	6,204	2,029
2. Self-confidence	88	6,375	1,883
9. Self-Control	88	6,727	1,679
10. Openness to Change	88	5,818	1,698

Source: Authors (data analysis performed by SPSS v.23).

These results suggest that engineering students have intrapersonal and activity development skills above the level of previous studies. As a consequence, we decided to increase the application of the BIP questionnaire to a representative sample of 314.

The soft skills shown in Table 1 do not change in the results. The other soft skills included in the BIP questionnaire are shown in Table 2. The results observed in it show that the scores on all the variables of the interpersonal skills area are below the average with respect to the reference group in which the mean was 5,750.

Table 2. Soft Skills results in the Interpersonal area and corresponding stanines of the whole group of students

Soft Skill	N	Mean	Standard deviation
3. Ability to work under pressure	314	5,675	1,614
4. Communication	314	5,675	1,614
5. Relationship building	314	3,427	0,888
6. Orientation to group work	314	3,306	1,034
7. Sensitivity	314	3,854	1,068
8. Sociability	314	4,789	1,571
11. Action Orientation	314	4,153	1,022

Source: Authors (data analysis performed by SPSS v.23).

The result is really interesting, since it indicates a lack in the development of soft skills in personal relationships for teamwork. This lack implies that the engineering curriculum should include training in teamwork or learning methodologies such as team-project-based learning, through which these soft skills can be developed. In order to anticipate this aspect, the questionnaire included another important question: whether the respondent was willing to be an active researcher by participating in the training project for the development of these skills. 62,1% showed interest by responding positively to the proposal to participate in a Soft Skills Training Laboratory. This aspect implies that undergraduates know their needs.

Reliability evidence

The study of the internal consistency (CI) of the BIP scales with the engineers' samples was measured by calculating Cronbach's alpha coefficient. As can be seen in the

Table 3, the reliability of the scales is very good in self-control, relationship building, orientation to teamwork, communication, emotional stability, ability to work under pressure, and self-confidence. The scales with moderate reliability are openness to change, sociability, sensitivity, and impression management. The action orientation scale has an unacceptable reliability.

Table 3. Reliability evidence of soft skill scales

Soft Skill	α	Number of items
1. Emotional stability	0,840	13
2. Self-confidence	0,810	12
3. Ability to work under pressure	0,750	13
4. Communication	0,740	11
5. Relationship building	0,840	15
6. Orientation to group work	0,870	13
7. Sensitivity	0,700	11
8. Sociability	0,510	11
9. Self-control	0,750	14
10. Openness to Change	0,690	10
11. Action Orientation	0,320	14
12. Impression Management	0,540	5

Source: Authors (data analysis performed by SPSS v.23).

Soft kills relation with gender and age

The age of the respondents was between 19 and 52 years, with a mean age of 25,04 years being the standard deviation of 3,83. It grouped the age of the sample participants from 19 to 25 and from 26 to 54 years in order to facilitate the subsequent statistical analysis of this variable with the other variables included in the study.

The Levene test for the difference in means between each of the variables observed and the gender is not significant in any case. T-Student was used with parametric variables, and, although it is true that there is some small difference, there were no significant differences between men and women. With non-parametric variables, two independent samples have been used: Mann-Whitney U (U-MW) and Kolmogorov-Smirnov (K-S).

Table 4. T-test for difference between means and Mann-Whitney U/ Kolmogorov Smirnov tests in gender in the intrapersonal area

Soft Skill	Levene	T	p
1. Emotional stability	0,535	-1,380	0,169
2. Self-confidence	0,719	- 0,126	0,900
3. Ability to work under pressure	0,157	0,577	0,564

Source: Authors (data analysis performed by SPSS v.23).

In the intrapersonal area, there are no significant differences in gender (Table 4) or age (Table 5). The 'p' associated with the statistical T is greater than the prefixed level of significance $\alpha = 0,05$. Results demonstrate that, in personal engineering-related skills, both men and women are equally prepared. This result suggests that the small number of women in technical degrees is not related to gender. The

Table 5. T-test for difference between means and Mann-Whitney U/ Kolmogorov Smirnoff tests in age in the intrapersonal area

Soft Skill	Levene	T	p
1. Emotional stability	0,621	-0,824	0,411
2. Self-confidence	0,167	-1,901	0,058
3. Ability to work under pressure	0,535	-1,380	0,169

Source: Authors (data analysis performed by SPSS v.23).

next analysis focused on the interpersonal area, regarding both gender (Table 6) and age (Table 7).

Table 6. T -test for difference between means and U-Mann Whithey/ Kolmogorov Smirnoff in gender in the Interpersonal Area

Soft Skill	Levene	T	p
4. Communication	0,011	U-MW: 0,510 K-S: 0,526	
5. Relationship building	0,343	- 1,018	0,310
6. Orientation to group work	0,742	- 0,665	0,507
7. Sensitivity	0,798	0,737	0,462
8. Sociability	0,326	0,109	0,789

Source: Authors (data analysis performed by SPSS v.23).

Table 7. T-test for difference between means and Mann-Whithey U/ Kolmogorov Smirnoff tests in age in the interpersonal area

Soft Skill	Levene	T	p
4. Communication	0,915	-1,006	0,315
5. Relationship building	0,849	-0,103	0,918
6. Orientation to group work	0,512	0,976	0,330
7. Sensitivity	0,621	-0,824	0,411
8. Sociability	0,020	U-MW: 0,625 K-S: 0,845	

Source: Authors (data analysis performed by SPSS v.23).

In both cases, gender and age, there are no significant differences between the groups in the interpersonal area, since the 'p' associated with the statistical T is greater than the prefixed level of significance $\alpha = 0,05$. Although an increase in the mean is observed as the age increases. Consequently, the skills necessary for team interactions in current engineering do not differ either. Finally, Tables 8 and 9 present the results of the activity development area.

Table 8. T-test for difference between means and Mann-Whitney U/ Kolmogorov Smirnoff tests in gender in the Activity Development Area

Soft Skill	Levene	T	p
9. Self-control	0,742	-0,665	0,507
11. Action Orientation	0,199	0,268	0,789

Source: Authors (data analysis performed by SPSS v.23).

Levene's test is not significant in any of the performed analyses. Consequently, the minimum differences that may exist between the different age and gender groups are not significant.

Table 9. T-test for difference between means and Mann-Whitney U/ Kolmogorov Smirnoff tests in age in the activity development area

Soft Skill	Levene	T	p
9. Self-control	0,512	0,976	0,330
11. Action Orientation	0,167	-1,901	0,058

Source: Authors (data analysis performed by SPSS v.23).

Conclusions

Detecting and measuring soft skills in people through questionnaires allows researchers to access relevant information to design syllabi adapted to the social and economic environment. In this study, the BIP questionnaire has been used to detect the soft skills in engineering students. This study shows the state of soft skills in Italian undergraduate engineering students: self-control, self-confidence, emotional stability and openness to change are above the average of different fields analyzed for the reference group. These skills are mainly related to the intrapersonal and activity development areas. Perhaps, these high scored skills are due to engineers' having a high demand for understanding physical concepts not directly related to people. Skills close to the average are the ability to work under pressure and communication. These skills are common for degree and master students. The skills below the average are sociability, action orientation, sensitivity, relationship building, and orientation to group work. These skills are only needed in a social context. Perhaps, the perception of an engineer working alone and using their own knowledge is a stereotype and can force people to avoid these skills. Consequently, it would be interesting to reinforce the social aspects of engineers.

Regarding self-control, flexibility, emotional stability, and self-confidence, statistical data indicate scores above the average. Thus, they were deemed to be far from one of the main objectives of the project: to design a university program that improves soft skills. Furthermore, the evaluated sample is considered significant to draw conclusions from this descriptive analysis.

It is interesting to observe how the engineers' soft skills that are above the means of the previous studies are the soft skills related to the intrapersonal and activity development areas. The results with the expanded group suggest that the soft skills related to the interpersonal area, such as teamwork, should be reinforced. This reinforcement can be done, either by specific training or through teamwork-oriented methodologies in the engineering curricula.

Engineers who participated in the research have more self-confidence than the reference sample, which means they rely fully on their ability to perform tasks in their field. They are active people who are confident when they face new challenges. Potential training in this area can be very useful. Self-confidence is something that is not usually hard-wired in us, and we must try to develop it. The results also show a great commitment in setting job goals and following projects. A good emotional adaptation to social situations is observed, since attitudes for a good problem solving are involved. The scores obtained for openness to change were similar to those of the reference sample. Probably, scores close to the average like this one are a common aspect of university students and, consequently, graduates. There is not a clear reason for this absence of differences between degrees. A possible cause may be that, at the intellectual level of a university, research provides a continuous change in the knowledge base. This implies that the technical contents of the subjects change over time. Therefore, in any area of knowledge, students assume these changes and, at the end of their studies, they know that they must be flexible and open to admit that, during their career, they will develop in a changing and innovative environment.

With the total sample and the rest of the variables, some conclusions have been drawn. The perception of the ability to work under pressure that engineers have of themselves is in the normative average. The subjects show that they are ready to deal with challenging tasks. This ability can be achieved by managing stress and correctly organizing the tasks to achieve the proposed objectives. These skills are relevant to explain a general openness to change; students are aware of the need to be flexible in the current job market.

An important aspect in the field of interpersonal relationships is the ability to communicate. Assertiveness is a way to firmly communicate one's rights. The score shows that the engineers of the sample are able to express positive and negative ideas and feelings in an open, honest, and direct way, thus finding themselves in the reference average. The data reflects the fact that sometimes they avoid social gatherings and have some difficulties in establishing personal contacts, particularly with strangers. This is the result of personal interviews with some students after obtaining the results. It is important to highlight that the perception of their social relationships is characterized by friendliness and respect, although the data also shows that in conversations it is possible that they are unable to understand the moods of those who are facing them and, therefore, may also have difficulty in understanding what their expectations are. From the results, it has been interpreted that there are some difficulties in working as a team compared to other people in the reference sample. They feel more comfortable and show greater efficiency by working individually and at their own pace. Currently, there is a greater demand for group thinking in many professional areas, which is why individuals with an individual focus must increase their range of behaviors in order to contribute to effective group collaboration when necessary. The engineers involved in this research are at an intermediate point between the two forms of orientation: to action and to the state. The statistical data indicate similar scores to the reference samples. The results are relevant for the future of engineering masters and degrees and can be used to determine the needs and adapt the syllabus for the future of engineering students.

Orientation to action favors the transformation of intention into action. On the other hand, orientation towards the state is characterized by having thoughts related to the attainment of a goal in the mind. It is important not to forget the fact that the

sample of engineers is heterogeneous. The study represents a relevant trend regarding the engineering curriculum degree, an opportunity to highlight the strengths and the weaknesses relative to implement the curriculum dedicated to engineers. The feature they share is the engineering degree, having in common an interest in the development of technical issues, but there are many types of engineering and, in turn, a large number of jobs and a wide range of functions to be performed.

The result of the research presented in the article generates a wide set of future works. The world of soft skills is in continuous growth. In the field of engineering, it is especially important. Traditionally, soft skills have been associated with the field of humanities, but their acquisition in engineering can lead to an increase in the efficiency and the addition of the 'human touch' of the resulting work.

Regarding soft skills, possible paths can be suitable for engineering should be sought. In our research, we have used soft skills related to the business environment, but some soft skills start to be associated with specific engineering fields, such as the 'structured mind' in the case of industrial engineering, or 'resilience' in the case of computing engineering. Matching soft skills with concrete engineering can adapt curricula to fit with specific engineers and companies' needs.

Regarding syllabi in engineering, it is necessary to look for ways to include soft skills. There is no efficient recipe. Including soft skills contents in all subjects will increase study hours or decrease the time dedicated to hard skills. Using teaching methods appropriate to specific soft skills could improve their acquisition by the students. This implies that research should be done on how to associate teaching methodologies with the necessary soft skills in engineering. This aspect is also a good field of work.

Finally, the detection and evaluation of soft skills is another issue that must be solved. Currently, for large groups, questionnaires like the BIP used in the article are the most efficient method. However, methods such as observation by experts, or empirical measurement of aspects such as the efficiency of team communication will be of great value in order to ensure and certify the acquisition soft skills.

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