Influence of Demand on Supplier Selection Using the Analytic Hierarchy Process: A Case Study Validation in the Textile Industry

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Abstract

Background: Supplier selection has emerged as an important activity regarding strategic purchasing with implications for the operational efficiency of both organisations and supply chains. Given the need to evaluate both qualitative and quantitative criteria for different supply alternatives, the decision-making process became more complex. **Objectives:** In the present work, an adapted Analytic Hierarchy Process model is proposed for supplier selection, which is being validated within the context of a textile company. The multi-criteria decision support model was coded in Python and encompasses criteria, cost, quality, delivery time, sustainability, and history. **Methods/Approach:** This model allocates weights to individual suppliers based on the diverse criteria considered. Four alternatives were considered as the chemical fabric dyeing pigment suppliers. Two different scenarios were considered to understand the influence of demand on the supplier selection problem. **Results:** The cost is the most valued criterion in the supplier selection (0.493 for Scenario 1 and 0.426 for Scenario 2). The second most important criterion for regular demand is quality (0.224), whereas, for the increased demand scenario, delivery time (0.301) is the second most impactful criterion. **Conclusions:** The application of the AHP for both tested scenarios resulted in a different priority, highlighting the adjustment capacity of the implemented model to different search parameterisations.

Keywords: Supplier Selection; Multicriteria Decision Model; AHP; Textile Industry

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Introduction

As companies strive to stay ahead of their competitors, they have come to realise that procurement is not just a cost-saving mechanism but also a strategic enabler of growth and sustainability (Aslani et al., 2008). Consequently, strategic purchasing assumes great relevance in any business, whether in the context of industrial, retail, or service. With the increased complexity of supply chains, more businesses have recently come to understand the critical role that procurement and strategic purchasing play in their operations (Aslani et al., 2008). Thus, it is important to understand the relationship between Procurement and Strategic Purchasing. Both concepts are closely related within the broader scope of supply chain management and are often used interchangeably (Bäckstrand et al., 2019; Ondoro et al., 2013).

While procurement primarily deals with operational tasks such as buying products and services, strategic purchasing emphasises a more strategic outlook involving market analysis, assessing supplier capabilities, identifying opportunities for collaboration and innovation, and optimising the supply chain to gain a competitive edge (Endo et al., 2017). Thus, it can be said that Procurement conventionally focuses on transactional activities, ensuring that a company obtains the required inputs at the right price, quality, and quantity. In contrast, strategic purchasing emphasises long-term partnerships with suppliers, innovation, risk management, and value creation rather than just cost savings (Ferreira & Silva, 2022). Then, strategic purchasing, a core component of procurement, involves aligning sourcing decisions with the long-term goals and objectives of Small and Medium Enterprises (SMEs). By adopting a strategic approach, SMEs can effectively manage their purchasing processes and drive sustainable growth (Bäckstrand et al., 2019; Klasa et al., 2018; Schütz et al., 2020). Key aspects include:

- Market Research and Analysis: Strategic purchasing begins with in-depth market research and analysis. Understanding market trends, supplier capabilities, and industry dynamics empowers SMEs to make informed purchasing decisions.
- Supplier Evaluation: Thorough evaluation of potential suppliers based on criteria such as quality, reliability, financial stability, and environmental practices ensures that SMEs partner with suppliers who share their values and vision.
- Long-term Cost Savings: By strategically negotiating contracts and building supplier relationships, SMEs can achieve long-term cost savings. This strategic foresight enables SMEs to be competitive while offering cost-effective products.

Supplier selection is a critical phase in the procurement process, where SMEs carefully evaluate and choose suppliers who can meet their specific needs and requirements. Key considerations for successful supplier selection include:

- Quality Assurance: Selecting suppliers with a proven track record of delivering high-quality goods and services ensures that SMEs can maintain consistent quality standards and meet customer expectations (Zimon & Zimon, 2019).
- Supply Chain Efficiency: Suppliers play a pivotal role in ensuring smooth supply chain operations. Selecting reliable and efficient suppliers contributes to the timely delivery of materials, reducing lead times and minimising disruptions (Gupta & Barua, 2017; Taherdoost & Brard, 2019). Also, the environmental sustainability of supply chains has gained a relevant weight (Huang et al., 2024).
- In today's rapidly evolving market, SMEs' sustainability hinges on their ability to innovate and adapt. This is where supplier selection plays a crucial role. Collaborating with innovative and adaptable suppliers allows SMEs to respond quickly to changing market demands and embrace new technologies, thereby ensuring their survival in the competitive business landscape.

Considering the increasing globalisation of markets, the supplier selection process is, therefore, a critical step of strategic purchasing because it requires ensuring quality, cost efficiency, reliability, risk management, innovation, and sustainability in developing partnerships between companies in the same supply chain. By carefully evaluating potential suppliers based on these criteria, companies can make informed decisions that support their strategic goals and drive overall success (Konys, 2019). This problem has a greater weight in the context of SMEs.

Supplier selection requires the identification of suitable suppliers whose services will be contracted and supplier evaluation, which rates the effectiveness of the selected suppliers (de Araújo et al., 2017). It should be considered a systematic process used to request and evaluate quotes and process the approved purchasing orders. The sourced suppliers should be compared based on qualitative and quantitative criteria (Fayos et al., 2022). It holds great importance in the overall SME supply chain management, allowing for the optimisation of resources, reducing costs, and maintaining an uninterrupted flow of materials, thereby enhancing their operational efficiency (Bienhaus & Haddud, 2018; de Araújo et al., 2017; Hernandez & Garcia, 2006). A key point to consider is cost optimisation since it allows SMEs to negotiate favourable terms with suppliers, securing cost-effective inputs and raw materials (Bevilacqua & Petroni, 2002). This cost optimisation contributes significantly to the financial health of SMEs, allowing them to allocate resources strategically and invest in growth areas (Endo et al., 2017). It also allows for improving supplier relationship management. Building strong and collaborative relationships with suppliers fosters mutual trust and encourages long-term partnerships. Close collaboration with suppliers enables SMEs to access innovative products, better terms, and early insights into market trends (Ellegaard & Andersen, 2015). Also, supplier diversification enhances supply chain resilience, mitigates disruptions and safeguards SMEs from unforeseen market fluctuations (Hawkins et al., 2020).

In the literature, several works focus on the relevance of integrating the supplier selection process in strategic purchasing. Based on the Kraljic Matrix, Garzon et al. (2019) created a green procurement technique for selecting and evaluating suppliers for a case study in the chemical industry. The purchasing strategy is based on the selection of suppliers that can contribute to the sustainable objectives preconised by the company. According to these authors, the selection criteria are mostly based on identifying environmental and social risks (Garzon et al., 2019). In Logistics 4.0, Hasan et al. (2020) suggested that a resilient supplier selection technique with heterogeneous information should be implemented by using simulation-based methods under different scenarios. The proposed method performs better than conventional methods in terms of robustness and adaptability to uncertain and dynamic situations.

According to Olanrewaju et al. (2020), the supplier selection decision is affected by key criteria such as pricing and discount quantity, delivery and lead time, commitment and capacity of the suppliers to accommodate the client requirements and the transport cost. Ferreira & Silva (2022) in their study, concluded that the most relevant criteria in supplier selection are (1) the quality of goods, (2) the compliance with delivery times, (3) price/cost, (4) supplier reputation and/or market positioning, (5) suppliers location, and (6) supplier performance history. Stevic (2017) have systematised the most noteworthy criteria that are commonly used in supplier selection. Criteria such as price, quality and delivery time still play a notorious role in the evaluation of suppliers. However, integrated approaches and computational methods need to be used to include a larger number of factors and criteria in the supplier evaluation process.

In this sense, SMEs require robust decision-making methods to identify the most suitable suppliers as well as other operational and tactical management decisions. Due to the increase in technology in companies, the entrepreneurial behaviour of managers has been reported in the literature, opening the possibility for companies to include support decision frameworks (de Freitas Michelin et al., 2023). The textile industry, the industrial sector under analysis in this work, is not an exception. The need to integrate data and information has resulted in the adoption of real-time production planning tools, considering the required resources and the timing in which they are needed for production. Therefore, decision support systems in this sector are crucial (Ćirković et al., 2022).

There are several decision-making approaches applied in supplier selection, including the Multiple-criteria Decision-Making (MCDM)/Multiple-criteria Decision Analysis (MCDA), Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Fuzzy Logic and Metaheuristics (Joy et al., 2023; Menon & Ravi, 2022). MCDM/MCDA refers to a family of methods developed in the 1960s and 1970s, including AHP, TOPSIS, and others. These methods offer SMEs a structured and consistent approach to evaluating potential suppliers based on diverse criteria, helping them make more informed and rational supplier selection decisions (Azhar et al., 2021). Most decision problems involve multiple, often conflicting, criteria or objectives, including quantitative, e.g., cost, time, and quality, and qualitative criteria, e.g., environmental impact or logistics integration. MCDM methods often involve sensitivity analysis to assess the robustness of decisions to changes in criteria weights or preferences (Al Hazza et al., 2022; Hamdan & Cheaitou, 2017).

The AHP, developed by Thomas L. Saaty in the 1970s, is a widely adopted method in decision-making and supplier selection processes (Saaty, 1987). AHP helps structure complex problems hierarchically, breaking them down into criteria and sub-criteria. Decision-makers compare these criteria and alternatives through pairwise comparisons, assigning numerical values to their relative importance. In SMEs, AHP provides a systematic approach to evaluate potential suppliers based on multiple criteria, enabling informed decisions and ranking suppliers according to overall performance. Parthiban et al. (2012) applied AHP to rank the suppliers of a group of components in the automotive manufacturing industry. Based on factors prioritisation, the suppliers' qualification and final selection were performed. Haldar et al. (2012) combined AHP, Quality Function Deployment (QFD), and Pre-emptive Goal Programming (PGP) techniques in supplier selection, considering a multi-objective criteria problem. The authors concluded that the three-method approach is applicable to decision-making processes in which the prioritisation of requirements must be conducted objectively. This scenario is prevalent in the majority of situations.

Gandhi et al. (2016) used the AHP technique to determine the relative importance/priorities of the success factors of SFs in green supply chain management adoption in manufacturing. The suggested framework was developed to assist industrial managers in crafting adaptable decision strategies for both short and long-term sustainable supply chain management. An MCDM approach was also introduced by Al Hazza et al. (2022) for suppliers' selection. The framework combines the application of the Delphi technique as a means of gathering data, along with the AHP application for data analysis. It allowed us to select the main criteria and assess the trade-offs among the feasible options based on those primary criteria.

TOPSIS, introduced by Hwang and Yoon in 1981, is a multi-criteria decision-making method that assesses alternatives based on their distance from the ideal and worst solutions (Jadidi et al., 2010). In the context of supplier selection, the TOPSIS method allows for identifying the supplier that best matches the ideal criteria while minimising the distance from the worst solution. By offering relative closeness scores for each supplier, it is possible to rank suppliers based on their similarity to the ideal solution (Hamdan & Cheaitou, 2017). Fuzzy logic, developed by Lotfi Zadeh in 1960, is a computational approach that handles uncertainty by allowing the assignment of degrees of membership to suppliers for each criterion. Unlike traditional binary logic, fuzzy logic accommodates vagueness and imprecision, making it valuable when dealing with qualitative and imprecise information in supplier evaluation for SMEs. Lima Junior et al. (2014) presented a comparative study between Fuzzy AHP and Fuzzy TOPSIS methods in the context of decision-making for supplier selection.

Methods were compared considering seven parameters, the most relevant the adequacy to changes of criteria and a number of criteria and alternative suppliers. It was verified that both techniques are adequate to deal with imprecision and subjectivity in supplier selection problems. There are other hybrid decision-making approaches that combine fuzzy logic and multicriteria analysis, allowing a holistic view of supplier performance, considering both qualitative factors, such as reputation, and quantitative factors, such as cost and delivery time. Metaheuristics are optimisation algorithms derived from principles such as evolutionary computation, swarm intelligence, and simulated annealing. For SMEs, metaheuristics provide a powerful and flexible approach to supplier selection, efficiently exploring large solution spaces to identify top-performing suppliers in a timely manner (Chen et al., 2020; Garg, 2021).

In this work, the AHP technique was selected since it is particularly used when there is an inherent subjectivity of the decision agent. The AHP model was adapted and programmed in Python to select the most suitable supplier in a company that operates in the textile sector for a specific dyeing pigment. The decision-making agents make their judgments by considering two different scenarios with distinct demand requirements presented at the time that the case study data was collected. The paper is divided into five sections. After an introduction, the AHP method for supplier selection is presented, and the description of the case study is provided in the material and methods section. The third section regards the implementation and validation of the AHP model. The last two sections correspond to the main results and discussion and the conclusions, respectively.

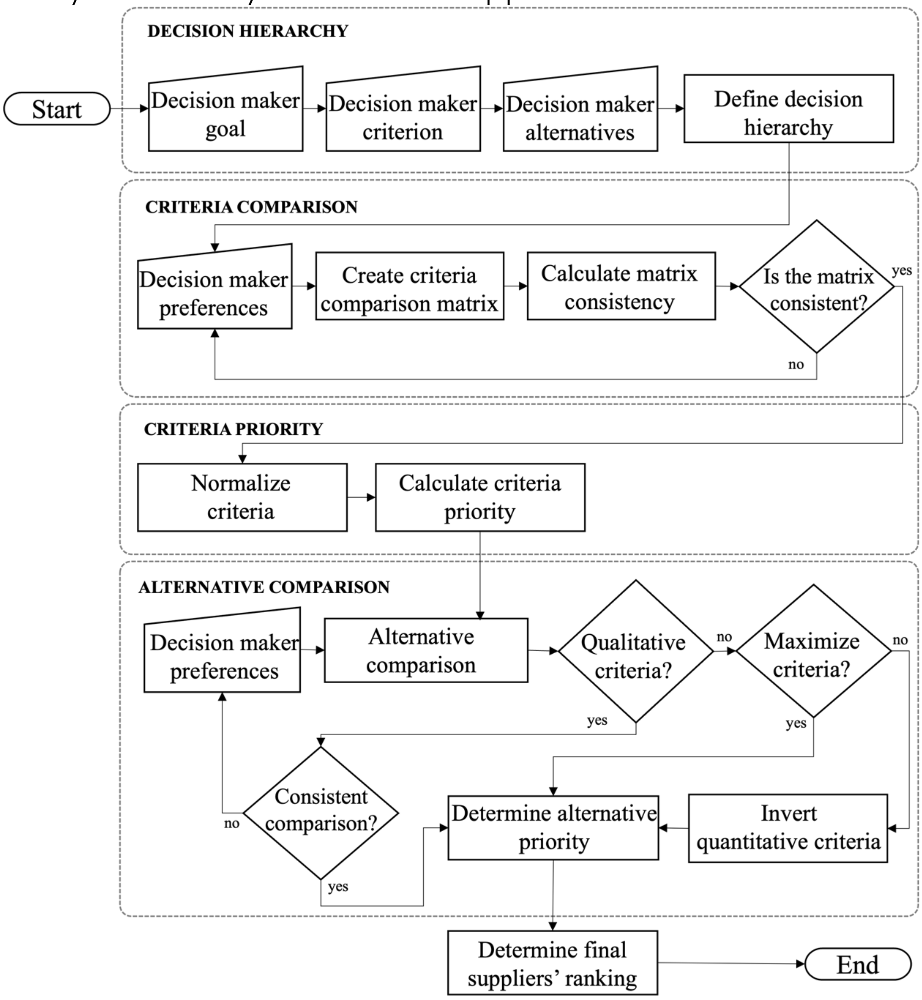
Methodology

This section describes the method used in supplier selection of fibre-reactive dye chemicals in a Portuguese textile company, which served as the case study for adapting the AHP method developed in the study.

Supplier Selection Analytic Hierarchy Process

In industry, problems are of great complexity, even for decision-makers with a high level of experience in the management and operational areas. AHP is a method that helps decision-making, allowing for a more informed decision. It is a multi-criteria decision method allowing the simultaneous consideration of well-defined (quantitative) and more subjective (qualitative) criteria. The AHP model used in this article is summarised, with calculations abstraction, in the flowchart exposed in Figure 1.

Figure 1
Analytic hierarchy flowchart for supplier selection



Source: Author's illustration

For a problem modelled by three levels to be correctly defined, it is necessary to create a well-structured Decision Hierarchy that considers the main objective of the problem (first level), the main criteria to consider (second level), as well as the available alternatives (third level) at the time of the decision. To do this, it is necessary to ask the decision-making agent what is the main objective (Who is the most suitable supplier to be selected?), what criteria should be taken into consideration when selecting a suitable supplier (cost, quality, delivery time, response flexibility or others), and also what alternatives (suppliers) are available at the time of the decision since the moment in which the decision is made usually has a great influence on the final decision.

The moment at which the decision is made will influence the criteria comparison made by the decision agent. In this phase, a comparison matrix is created based on the preferences established by the decision agent. To make the comparison, the decision-maker uses a Saaty scale (Saaty, 1987), also known as the comparative preference scale, which is a technique used in multi-criteria analysis to evaluate and compare the relative importance of different criteria or alternatives in a decision-making process. It allows decision-makers to express their preferences comparatively between pairs of criteria or alternatives, assigning numerical values that represent the intensity of the relative preference. To check whether the expressed preferences are stable and logical, without contradictions, the matrix consistency is verified to ensure greater reliability in the presented decision suggestions. If the matrix is not consistent, it is necessary to request a review from the decision-making agent.

If the matrix is mathematically consistent, a vector with the criteria priority is created. In this phase, a relative priority is created for each criterion, and the criteria are normalised so that the sum of their values corresponds to the unit value.

Then, the alternative comparison is made, allowing a pairwise comparison of the different suppliers for each of the defined criteria. At this stage, it is necessary to understand the type of criterion and its objective so that the decision maker can make the comparison as precisely as possible. If the criterion is qualitative, the comparison between alternatives is performed similarly to the comparison between criteria. When the criterion is quantitative, it is necessary first to check whether the objective is minimisation or maximisation to adjust the normalisation of the criterion in the defined direction. In other words, for example, if the delivery time of an item is to be minimised, the supplier with the shortest delivery time must be the one with the highest weight in the respective criterion, normalising the respective inverse value. If the criterion aims to maximise, the numerical values are normalised so that the respective sum totals the value one. A priority vector is then created for each of the different criteria.

Finally, the result of multiplying the priority vectors of each criterion (as columns of the matrix) and the priority matrix of the alternatives leads to a final classification of alternatives, where the highest value corresponds to the most suitable supplier for the objective defined by the agent of decision.

Case study description

To evaluate the performance and sensitivity of the implemented AHP model for the supplier selection problem, a case study was used in an industrial context where two different scenarios of demand for a pigment are addressed. This was obtained through a real case of an SME located in the north of Portugal, which has 77 employees and has operated in the textile area for over twenty years. It is dedicated to textile dyeing, more specifically in the business areas of home decor, swimwear, and sportswear, among others. Dyeing is a chemical process that changes the colour of the textile fibre through the application of coloured materials. One of the products most used by the company, which was selected for this study, consists of a fibre-reactive dye, which is mostly used in dyeing cotton or linen fabric.

The company has four specific suppliers to provide the pigment; however, for reasons of confidentiality, these will be identified with the letters A to D. The company's decision-maker selected five criteria to analyse which supplier would be most suitable to supply the company decision. Table 1 presents a definition and parameterisation of the criteria defined by the company's decision-making agent. Cost (monetary units) and quality of the product, history/relationship with the company (years), delivery time (days) and the sustainability conditions under which the pigment is produced are the criteria indicated by the decision agent to be included in the decision support model.

Criteria can be quantitative or qualitative. In qualitative criteria, it is possible for the decision-maker to define a level of preference between two different suppliers. For example, for the sustainability criterion, supplier B may be a little more suitable than C (preference level). In quantitative criteria, it is possible to obtain exact information about a given criterion since known numerical values, such as the cost of the pigment in each period for different suppliers, represent them. It is also possible to define a maximisation or minimisation objective that is associated with a specific criterion. An example is the cost since a supplier that charges a lower cost is more attractive than others that have higher costs if the objective is finding a product with a competitive cost. However, this parameterisation only refers to an individual criterion, not considering the behaviour of other criteria.

Table 1
Criteria to select a more suitable supplier for textile pigment

Criteria	Type	Objective	Definition
Cost			Cost is defined as the amount the company is willing to pay to acquire a unit of pigment, including all acquisition and transportation costs.
Quality			Quality refers to the level of quality of the product delivered by the supplier. Several aspects classify the level of quality, trying to categorise products by their level of compliance with quality requirements defined by customers and the company.
Delivery time			Delivery time is the effective time between ordering the pigment from the supplier and the moment it is delivered to the company.
History			History refers to the number of years that a given supplier has collaborated with the company. Longer collaborations are an indicator that the supplier is trustworthy and offers quality products. This indicator is used to assess reliability and consistency over time.
Sustainability			Sustainability refers to the set of good practices and techniques that suppliers follow in the production of pigment, namely care in creating more sustainable and environmentally friendly packaging, use of renewable energy sources, and selection of renewable materials.

Quantitative   Qualitative   Minimise   Maximise   Preference level

Source: Authors

Two different scenarios were considered to understand the sensitivity of the AHP model. The comparison of alternatives will not be changed, as they are close in time, and there is no variation in the quantitative criteria and the comparison between alternatives. Only the criteria comparison will be changed.

In the first scenario (Scenario 1), the company has low customer demand and, therefore, enough time to acquire the pigment, so cost will be the most important criterion. In an alternative scenario (Scenario 2), the company received an urgent request from an important customer with whom it had a long-term relationship, and demand for the pigment consequently increased.

Although the company continues to prioritise cost when making the decision to avoid production delays, it already manages its preferences regarding delivery times differently. The data concerning these scenarios are presented in more detail in the validation of the case study (Section 3) and in the discussion of the results (Section 4).

Model Implementation and Validation

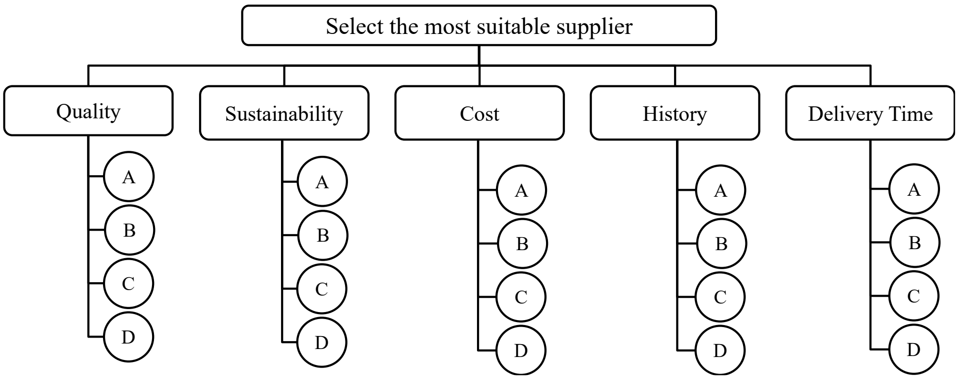
In this section, the developed AHP model for the supplier selection problem will be presented and validated. This model will be applied to both, as detailed in Section 2.2. The practical validation of the AHP method will be divided into the different phases depicted in the Figure 1 flowchart for a clearer presentation of the results.

The implemented model was developed in Python programming language without using any specific Python library regarding the AHP model. Indeed, this decision enabled the definition of the entire algorithm instead of relying on a previously developed framework that could be used as a black box, and the focus would be the result, disregarding how it was achieved. For a better discussion and clarification of intermediate results, an exploratory analysis of the data and mathematical representations will be used. In this way, it is possible to highlight the relationship between the different criteria and alternatives attributed by the decision agent for the different analysed scenarios.

Decision Hierarchy

The main objective in defining a decision hierarchy is to visualise the problem in an integrated manner while simultaneously addressing the sub-problems in a more detailed way. This allows for a global view of how sub-problems at lower levels affect higher levels in the hierarchy. The defined hierarchy is shown in Figure 2.

Figure 2
AHP Hierarchy for suppliers' selection scheme



Source: Author's illustration

The first level of the hierarchy allows for defining the global objective of the model, in this case, the selection of the most suitable supplier according to the preferences of the decision-maker for the acquisition of the preferred pigment. For the second level, five distinct criteria are defined that were considered the most relevant by the company's decision-making agent, namely cost, product quality, history with suppliers, delivery time and the sustainability conditions that suppliers consider in the pigment production.

The last level of the three-level hierarchy defines the alternatives available at the time of decision-making. In this case, it refers to the different suppliers available to supply the company with the pigment referred to.

For reasons of confidentiality, these are referred to as suppliers A, B, C, and D. It is important to highlight that to make a fair comparison between levels and elements of the hierarchy, it is necessary to use a common unit of measurement, such as a weighting factor.

Criteria Comparison

To enable a comparison between each criterion and establish a priority among all selected criteria by the decision agent, one needs to assign a preference level between criteria pairs. By using such comparative attributes, it is possible to establish the priority and understand which criteria the company most values.

Based on Saaty's fundamental scale (Saaty, 1987), the decision agent uses values between 1 and 9 to establish the qualitative relationship among all criteria. Thus, 1 indicates that both criteria are equally important, 3 indicates that the first is slightly more important than the second, and 5 sets a higher importance level. This qualitative measure grows up to 9, where one criterion is extremely important compared to the other.

Nevertheless, intermediate values are also allowed. Figure 3 presents a criterion pairwise comparison where the intensity of the colour (dark blue) indicates a more important criterion. In the opposite direction, the inversed value is used. Indeed, as observable in the figure, the pair Cost-Sustainability has a value of 7, meaning that the cost is very important when compared to sustainability. In the opposite pair, Sustainability-Cost, the presented value is 0.143 (≈1/7 rounded by three decimal places).

Figure 3
Criteria pairwise comparison matrix for Scenario 1

	Quality	Sustainability	Cost	History	Delivery Time
Quality	1	4	0.333	2	3
Sustainability	0.25	1	0.143	0.333	0.5
Cost	3	7	1	4	5
History	0.5	3	0.25	1	2
Delivery Time	0.333	2	0.2	0.5	1

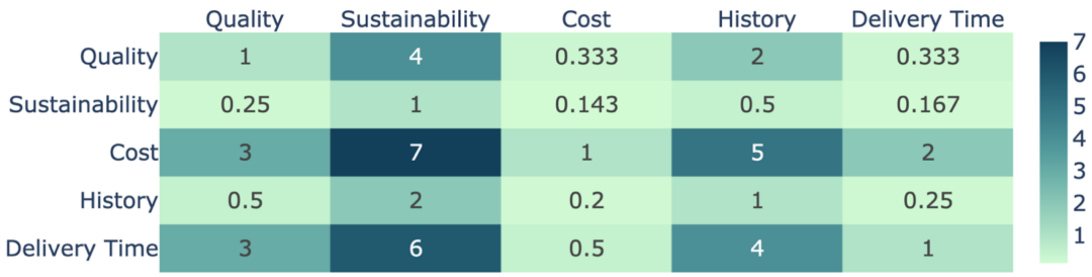
Source: Author's illustration

By analysing the comparison matrix presented in Figure 3, it is observable that the Cost is an important criterion since it has values greater than 1 when compared to the remaining criteria. Quality is also an important criterion since all values are greater than 1 for all criteria, with cost being the only exception.

On the other hand, sustainability may be seen as the least important criterion since all comparison pairs have values smaller than 1. This comparison matrix demonstrates the criteria comparison for scenario 1, in which the company had low customer demand and sufficient time to obtain the pigment.

Figure 4 represents the comparison matrix for the second scenario. Here, the customer demand for the pigment was higher. The cost criteria continue to be the most important since they have greater values than the remaining criteria. Due to the need to get the pigment quicker to satisfy the demand, in this scenario, the Delivery Time is the second most important criterion, surpassing the Quality (of scenario 1). Sustainability continues to be a minor valuable criterion.

Figure 4
Criteria pairwise comparison matrix for Scenario 2



Source: Author's illustration

By analysing Figure 3 and Figure 4, one may observe that in both scenarios, cost is the most important criterion from the decision-maker's perspective. However, the urgent need for pigment from suppliers to fulfil the customer's needs makes the difference in the second most important criterion, the Delivery Time for Scenario 2, whereas, in the first scenario, it is the Quality of the supplied pigment.

Criteria Priority

In the previous section, an empirical comparison was made to identify the most important criteria for each scenario. Indeed, in this section, the goal is to numerically define the relative priority of each criterion on a scale from zero to one. Under the linear algebra subject, this procedure corresponds to determining the highest eigenvalue and its corresponding eigenvector. Then, this vector is normalized. An approximation may be performed with good results to mathematically simplify the process of calculating the eigenvalue and eigenvector.

For such a process, it is necessary to do a column-wise sum for the matrix defined in Figure 3, and then each element of a column is divided by its sum. To obtain the eigenvector approximation, the arithmetic mean is calculated in a line-wise format of the normalised correlation matrix, obtaining the priority vector for the criteria. As an example, one needs to do the sum of each column, which is 5.083 for the first column ($5.083 \approx 1 + 1/4 + 3 + 1/2 + 1/3$), as depicted in Table 2.

Table 2
Criteria normalisation process for Scenario 1

Criteria	Quality	Sustainability	Cost	History	Delivery Time
Quality	1	4	0.333	2	3
Sustainability	0.25	1	0.143	0.333	0.5
Cost	3	7	1	4	5
History	0.5	3	0.25	1	2
Delivery Time	0.333	2	0.2	0.5	1
Sum (column)	5.083	17	1.926	7.833	11.5

Source: Authors

Then, each element of this example column is divided by its sum, obtaining 0.197 for the first element (0.197 ≈ 1/5.083). After performing these steps for the entire matrix, the obtained results are presented in Table 3.

Table 3
Criteria eigenvector approximation for Scenario 1

Criteria	Quality	Sustainability	Cost	History	Delivery Time	Mean (line)
Quality	0.197	0.235	0.173	0.255	0.261	0.224
Sustainability	0.049	0.059	0.074	0.043	0.043	0.054
Cost	0.590	0.412	0.519	0.511	0.435	0.493
History	0.098	0.176	0.130	0.128	0.174	0.141
Delivery Time	0.066	0.118	0.104	0.064	0.087	0.088

Source: Authors

After normalising and determining the preference vector, it is necessary to check if the matrix is consistent, i.e., ensure that the matrix complies with a mathematical indicator named consistency ratio. This ratio validates if the performed comparison is adequate. According to Saaty's definition, this ratio should not be greater than 0.1. Let us consider the matrix $A\, with\, the\, criteria\, preferences\, and\, a\, vector\, with$ the corresponding priorities (Saaty, 1987).

Equation (1) may be used to approximate the highest eigenvalue lambda sub m a. x associated with the eigenvector.

$$A \times w = \lambda_{max} \times w \qquad (1)$$

The consistency index (CI) is defined through Equation (2), which uses the obtained λ_{max} and the number n of criteria.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (2)$$

To determine the consistency ratio, one needs to calculate the ratio between CI and a pre-defined random consistency index (RCI). The RCI was defined by Saaty, (1987). According to the author, these values may only be used when the comparison is done on three or more criteria. Indeed, the AHP method intents to support a multi-criteria decision. The consistency ratio (CR) is calculated according to Equation (3).

$$CR = \frac{CI}{RCI} \qquad (3)$$

Using the Root Mean Squared Error, where x_i is i[th] value in vector w and y_i is the i[th] value of the eigenvector associated to the highest eigenvalue, the error can be obtained, as presented by Equation (4).

$$RMSE = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{n}(x_i - y_i)^2\right)} \qquad (4)$$

This process to evaluate the matrix consistency was then applied as presented in Table 4. Thus, the matrix A with the criteria preferences and the vector w with the corresponding priorities were used to calculate λ_{max}. By replacing the values, a value of $\lambda_{max} = 5.079$ was obtained. For $n = 5$ (number of defined criteria) and $\lambda_{max} = 5.079$, the value of CI is approximately 0.02. The calculation of CI used an approximation of the highest eigenvalue, which was obtained from the calculated eigenvector.

Table 4
Consistency of criteria matrix evaluation for Scenario 1

Procedure steps	Application of the mathematical procedure
Identification of criteria preferences and priorities	$A = \begin{bmatrix} 1 & 4 & 1/3 & 2 & 3 \\ 1/4 & 1 & 1/7 & 1/3 & 1/2 \\ 3 & 7 & 1 & 4 & 5 \\ 1/2 & 3 & 1/4 & 1 & 2 \\ 1/3 & 2 & 1/5 & 1/2 & 1 \end{bmatrix} \quad w = \begin{bmatrix} 0.224 \\ 0.054 \\ 0.493 \\ 0.141 \\ 0.088 \end{bmatrix}$
Calculation of the highest eigenvalue	$\begin{bmatrix} 1 & 4 & 1/3 & 2 & 3 \\ 1/4 & 1 & 1/7 & 1/3 & 1/2 \\ 3 & 7 & 1 & 4 & 5 \\ 1/2 & 3 & 1/4 & 1 & 2 \\ 1/3 & 2 & 1/5 & 1/2 & 1 \end{bmatrix} \begin{bmatrix} 0.224 \\ 0.054 \\ 0.493 \\ 0.141 \\ 0.088 \end{bmatrix} = \lambda_{max} \begin{bmatrix} 0.224 \\ 0.054 \\ 0.493 \\ 0.141 \\ 0.088 \end{bmatrix} \Leftrightarrow$ $\Leftrightarrow \lambda_{max} = average \left\{ \frac{1.148}{0.224}; \frac{0.271}{0.054}; \frac{2.544}{0.493}; \frac{0.713}{0.141}; \frac{0.439}{0.088} \right\} \approx 5.079$
Calculation of CI	$CI = \frac{5.079 - 5}{5 - 1} \approx 0.02$
Calculation of CR	$CR = \frac{0.02}{1.12} \approx 0.018$

Source: Authors

By using the open-source *Scilab* software, it is possible to calculate the eigenvector associated to the highest eigenvalue using the *spec* command. The obtained values will be {0.392; 0.093; 0.870; 0.243; 0.150} with an eigenvalue of 5.078.

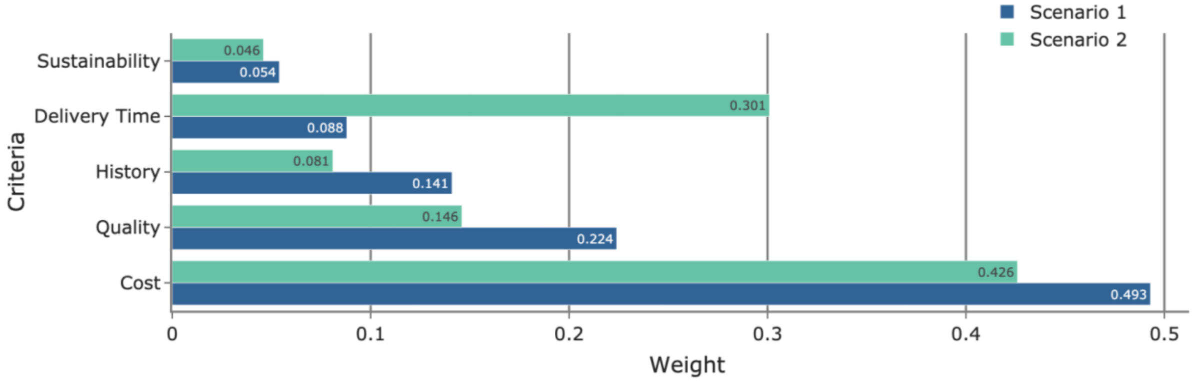
For this example, all remaining (four) eigenvalues are complex numbers, whereas associated eigenvectors also have complex numbers. By normalising the eigenvector, the final vector is {0.224; 0.053; 0.499; 0.139; 0.086}.

Based on the pre-defined values of RCI established by Saaty (1987), for five criteria with a cap R, cap C, and cap Iteria with a $RCI = 1.12$, CR is approximately 0.018, which is less than 0.1. Thus, the criteria comparison matrix is consistent. Using the Root Mean Squared Error, the obtained error is about 0.003 (0.3%). The complexity of determining such values is a disadvantage in computational terms since the results will be approximately the same.

The same procedure is applied for the second scenario (Scenario 2). The criteria relative priority results for both scenarios are presented in Figure 5.

Cost is the most important criterion in both scenarios. Regarding Scenario 1, Cost is followed by Quality. The least important criterion is Sustainability, with a relative importance of 5.4%. For Scenario 2, due to the need to acquire pigment to fulfil the orders, cost continues to be the most important criterion, but with a small decrease in its importance. Delivery Time becomes the second most important, surpassing Quality. Sustainability is the least important criterion, and its importance has decreased.

Figure 5
Criteria relative priority for Scenario 1 and Scenario 2



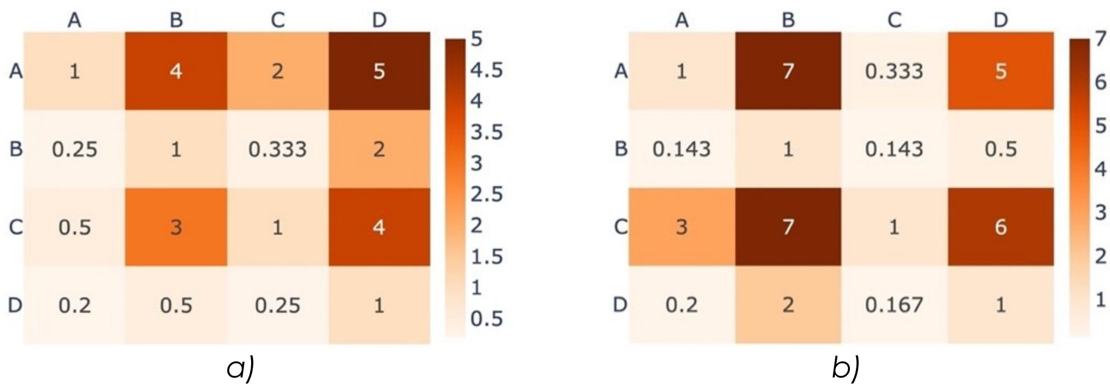
Source: Author's illustration

Alternative Comparison

In the alternative comparison phase, the aim is to compare the selected alternatives through all criteria. According to each type of criterion, there are different methods to do this alternative comparison. Indeed, for qualitative criteria (like quality or sustainability), the process is equivalent to the comparison of criteria presented in the previous step. Thus, for this type of criteria, the decision-maker needs to set values in a comparison matrix that, instead of having the criteria, has all alternatives. According to Saaty's scale, comparison values are set and normalised, and an alternative vector is obtained. For both scenarios 1 and 2, the selected alternatives presented the same characteristics.

Figure 6a and Figure 6b present the qualitative comparison matrices for the quality and sustainability criteria, respectively. For quality, it is observed that supplier A has the highest values, being above 1. Supplier C is, for the quality criterion, the second most suitable supplier since it only loses to supplier A (the only value that is below 1). In contrast, for the Sustainability criterion, this order is reversed, with C being the more suitable supplier. Both matrices are consistent since their consistency ratio is 0.018 and 0.058, respectively, meaning that both values are smaller than 0.1.

Figure 6
Qualitative alternative pairwise comparison matrices: a) Quality; b) Sustainability.

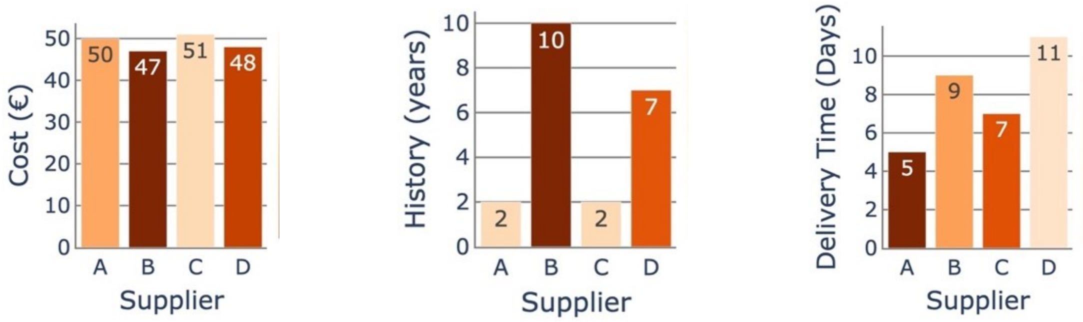


Source: Author's illustration

For quantitative criteria, the process for creating a comparison vector is slightly different since, for such types of criteria, there is no ambiguity from the decision agent.

Indeed, for these criteria, a numerical value is known and used to make a comparison. For each criterion, there is also the need to understand if the goal is to maximise or to minimise the results. In the case of, for example, History, the goal is to valorise suppliers that have a longer commercial relationship with the company. Thus, the goal is to maximise this criterion. Cost and Delivery Time are examples of minimisation criteria, i.e., the goal is to increase the importance of suppliers that have lower costs and lower Delivery Times. The quantitative criteria are presented in Figure 7.

Figure 7
Quantitative alternative comparison by: a) Cost; b) History; c) Delivery Time.



a) *b)* *c)*
Source: Author's illustration

The process for defining the comparison vector within quantitative criteria is to execute the normalisation of values. Bigger values mean that such a supplier (alternative) has better results than those with lower ones. However, when the goal is to minimise, there is an initial step to invert the defined values.

Taking the Delivering Time as an example, by inverting the highest value, it becomes 1 over 11, almost equal to 0.091 and the same for the lowest 1 over 5, almost equal to 0.200. With this intermediate step, smaller values have higher importance after normalisation.

Final Ranking

After determining all comparison vectors between suppliers for each criterion, the goal is to create a global ranking system to understand who the most suitable supplier is for satisfying the pigment company's needs. Indeed, the result is a ranking defined according to the decision agent preferences of selected criteria and alternatives.

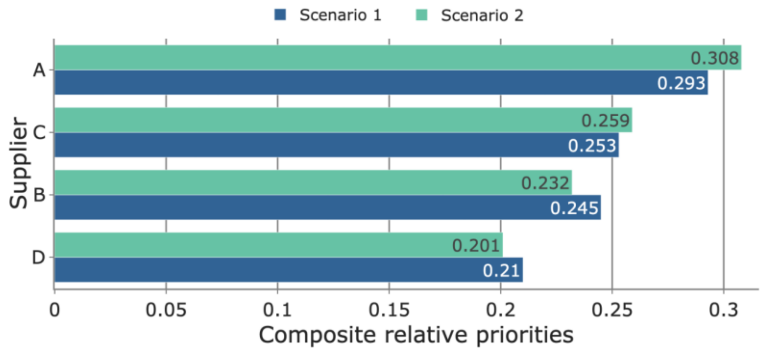
To obtain such a final ranking, it is necessary to create a matrix where each column contains the priority vector for the alternatives for each criterion. This matrix is then multiplied by the criteria comparison vector determined in the first step. The alternative comparison matrix is represented as M, where lines are suppliers A, B, C, and D, and columns are the criteria Quality, Sustainability, Cost, History, and Delivery Time, in this order. Vector *w* represents the criteria importance vector for Scenario 1.

By multiplying matrix M by vector w, it is obtained the final ranking vector RS1, as presented by Equation (5). For Scenario 2, the same process is executed to obtain the final alternative ranking vector.

$$RS1 = M \times w \tag{5}$$

Figure 8 depicts the results for both scenarios. Despite the difference between both cases, the final order to select suppliers has not changed. However, the company's need for the pigment intensifies the rank of supplier A to the detriment of the remaining ones since, in this second scenario, Delivery Time is the second most important criterion, and the Cost differences to other suppliers are not very different, since the variation coefficient is low (being Cost the most important criteria). For Scenario 1, supplier A obtained the highest priority with a relative value of 0.293. This is followed by supplier C with 0.253. Supplier D is close to C with a relative value of 0.245. Finally, Supplier D is in the last position with a relative priority of 0.201.

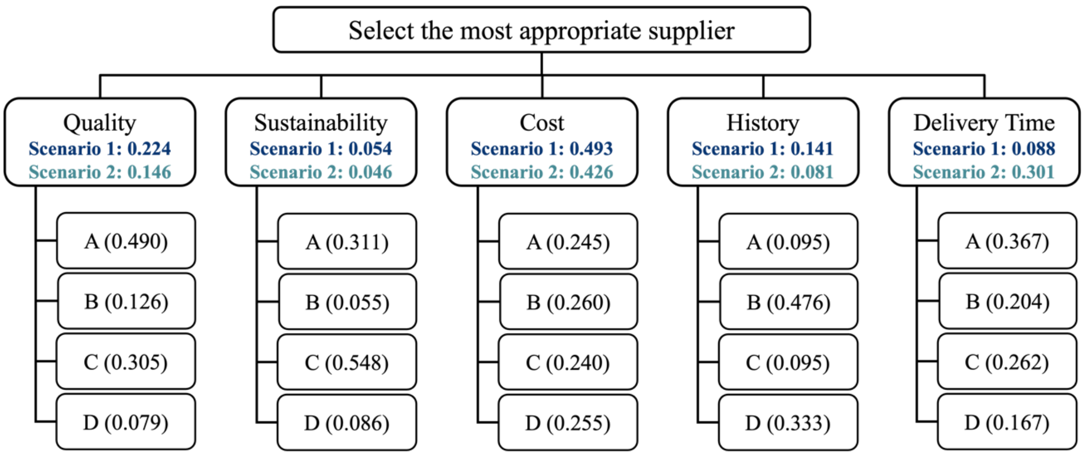
Figure 8
Final suppliers' ranking for Scenario 1 and Scenario 2



Source: Author's illustration

For Scenario 2, the final order remains the same, but the relative priority values change. Indeed, supplier A distances itself from the others since, in this scenario, this supplier stands out by providing the shortest delivery time. By applying the AHP to support the decision of the decision agent, which considers the preferences and requirements of the decision agent, the most suitable supplier is supplier A. According to the selected criteria, this is the one that better satisfies the pigment company's needs. In Figure 9, the final AHP hierarchy is presented with the relative importance values for criteria and alternatives.

Figure 9
Final weighting AHP hierarchy for suppliers' selection



Source: Author's illustration

Despite the final supplier rank, the results being the same, there are some differences related to each scenario-specific requirement, as highlighted in Figure 9. Indeed, the most important criterion, Cost, was reduced by 13.6% between scenarios. Delivery time, which changes from the 4th to the 2nd position between scenarios, was increased by 242%. Quality, on the other hand, went from the 2nd position to the 3rd with a percentual decrease of 34.8%. History was also decreased, in terms of its importance, by 42.6%. Finally, Sustainability maintained the same last position, but its importance decreased by 14.8%.

Results

Although the result is slightly different, supplier A is the most suitable supplier for the pigment above for both presented scenarios according to the decision maker's preferences. In this section, a critical analysis of the results will be carried out to demonstrate how the criteria and demand influence the final decision to recommend supplier A.

It is important to highlight that the AHP model is a multi-criteria method that presents decision-making recommendations, allowing the decision-maker to achieve more informed and well-founded decisions within the organisation. In the first phase, and after normalising the criteria to allow a fairer comparison, it is possible to observe the values of the different criteria for the different suppliers without considering any weighting. At this stage, a comparison is made without considering the influence of demand at the time of the decision (Figure 10), as described in the two presented scenarios. In other words, the sum of the weighting of each criterion must total one.

Figure 10
Final suppliers' ranking comparison without criteria weighting

Source: Author’s illustration

For the Cost criterion, it is possible to verify that all suppliers present a normalised value between 0.2 and 0.3, which in practice represents an average and median of €49 per industrial unit of pigment, a population standard deviation of €1.581, and a low coefficient of variation (about 3.2%).

In the Sustainability criterion, supplier C stands out as the supplier with the most sustainable practices in pigment manufacturing, with a value between 0.5 and 0.6, while supplier B is the one with the least sustainable practices, with a value below 0.1. It is also possible to verify that supplier A stands out from the others due to its Quality (approximately 0.5) and Delivery Time (between 0.3 and 0.4).

On the other hand, customer D presents the lowest Quality values (less than 0.1) and Delivery Time (less than 0.2). In terms of Delivery Time, suppliers have an average median of 8 days for delivery and a standard deviation of 2.236 days, which is reflected in a coefficient of variation of approximately 28%.

Regarding the History that the supplier has with the company, it is possible to verify that suppliers A and C are suppliers with a very young relationship with the company (approximately 0.1).

In contrast, suppliers B and D have a more mature and long relationship with the company, meaning their value is higher, between 0.3 and 0.4 and approximately 0.5, respectively. This difference in years of partnership is evidenced by the high coefficient of variation (65.1%). The history/relationship criterion with the supplier presents an average of 5.25 years, a median of 4.5 years, and a standard deviation of 3.419 years. Please note that the standard deviation of the population was used since all suppliers (A to D) selected by the decision agent to be part of the model were analysed (Table 5).

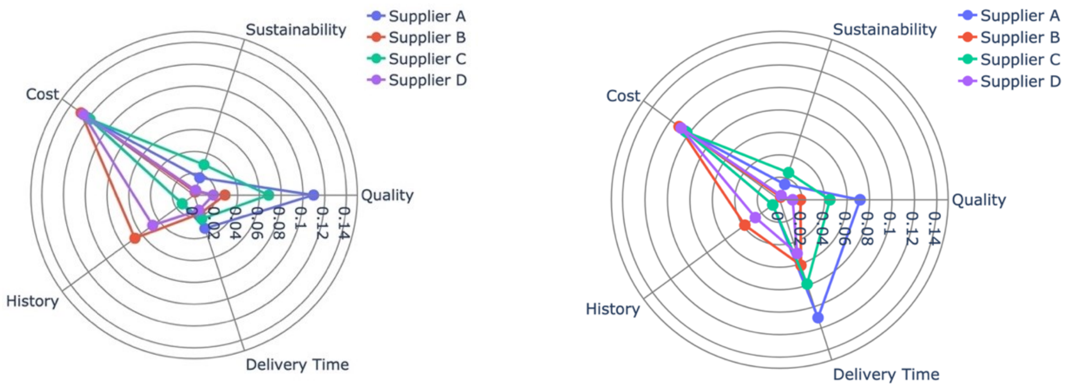
Table 5
Measures of dispersion and central tendency of quantitative criteria

Quantitative Criterion	Median	Mean	Std. Dev.	Min	Max	Variation Coefficient
Cost (€)	49	49	1.58	47	51	0.032
History (years)	4.50	5.25	3.42	2	10	0.651
Delivery Time (days)	8	8	2.24	5	11	0.280

Source: Authors

The radar graphs presented in Figure 11 consider not only the comparison between different suppliers but also the weight attributed to the criteria by the decision agent in the two presented real scenarios. In other words, the sum of the weighted criteria and the weighted alternatives must be equal to one. In the first scenario (Figure 11a)), Demand is relatively low, so the company's main objective is to acquire a very good quality pigment at the lowest possible Cost. In a second scenario with greater demand ((Figure 11b), Cost continues to be a highly valued criterion, as does Quality. However, the Delivery Time becomes more important when selecting the most suitable supplier. The Sustainability criterion, even for the supplier most concerned about sustainable practices, now has a small weighting (less than 0.04) for both scenarios as it is not yet one of the company's biggest concerns, complying with the stipulated requirements.

Figure 11
Final suppliers' ranking with criteria weighting: a) Scenario 1; b) Scenario 2.



a) *b)*

Source: Author's illustration

In both scenarios, Cost is a highly valued criterion. However, the company is now slightly more willing to prioritize the Delivery Time criterion over Cost (less than 0.12 to less than 0.14). When demand is higher, the company is willing to purchase pigment from suppliers of slightly lower quality (less than 0.08 instead of 0.12) if it continues to meet quality requirements.

It should be noted that the decision agent only included in the decision model suppliers that meet the requirements imposed by the company and customers for all criteria. Hence, a reduction in them never implies non-compliance with the proposed requirements. The number of years of partnership between the company and suppliers becomes slightly less important (less than 0.06 to less than 0.04) since one of the most priority criteria becomes the Delivery Time.

Despite the mentioned observations, supplier A proves to be the most suitable to supply the company, despite being a supplier with a relatively young partnership with the company. This decision makes sense since supplier A is strong in the three main criteria valued by the company: Cost, Quality and Delivery Time. Supplier A is the most suitable of the four alternatives in terms of Quality and Delivery Time, and despite not being the one with the cheapest Cost, it has a competitive cost. This result may be an indicator that companies, to become competitive today, cannot only have the reduction of the Cost as their main objective but also criteria such as Quality and Delivery Time.

Conclusion

In this paper, a multi-criteria AHP model is implemented for the supplier selection problem. This model allows deciding which supplier is most suitable according to the preferences of the decision-maker of a company that operates in the textile area and intends to acquire a specific textile pigment for its production process. Two demand scenarios were analysed in a real application case to understand the influence of demand on decision-making through the proposed model.

In Scenario 1, the company's demand was low, meaning that Cost and Quality were prioritised as the main criteria for decision-making. For Scenario 2, demand was greater, and customer orders were more urgent. Hence, the Delivery Time criterion had to be prioritised, resulting in a slight reduction in the prioritisation of Quality and Cost. Thus, the main outcome resulted in Cost being the most valued criterion in the supplier selection (0.493 for Scenario 1 and 0.426 for Scenario 2). Nowadays, it may no longer make sense to use Cost reduction as the main or only criterion to achieve competitive solutions in the selection of suppliers since customers around the world have increasingly valued the criteria of Quality and Delivery Time due to fluctuations in demand triggered by customers' needs and consequently felt by companies. Despite the differences in demand, supplier A proved to be the most suitable for satisfying both scenarios. Notwithstanding being a supplier with a young relationship with the company, it is strong in the three criteria most valued by the company, that is, Cost, Quality, and Delivery Time.

Regarding the practical and scientific contribution of the present work, this study aims to implement a mathematical approach based on the adaptation of one of the most used methods from the literature, the AHP method, to be used as an adjusted decision support system that deals with many criteria and supplier alternatives. This will allow adequate management choices and justify decision-making in the industrial environment.

The main limitation of the implemented approach relies on subjective judgments from decision-makers, which can introduce bias into the process. Thus, in the next iteration of the work, a framework will be created, allowing different evaluators to assign different weights to the considered criteria. Another limitation concerns the difficulty in obtaining accurate data, especially for qualitative factors like supplier reliability or responsiveness. Lastly, as the number of criteria and alternatives increases, the complexity of pairwise comparisons grows exponentially, making the process more time-consuming and resource intensive.

In future research, it will be important to create software with a user-friendly interface that allows effective and efficient communication with the decision agent, autonomous characterisation and parameterisation of the problem, and the analysis and visualisation of the decision process in real time. On the other hand, the decision process deals with subjective data determined by the decision agent that may present inconsistencies. At this point, these inconsistencies are solved by requesting changes to the comparison matrix provided by the decision agent, which will be the natural process if it is not possible mathematically and automatically to make the matrix consistent. In other words, it would be important to try to make the matrix consistent through mathematical procedures, when possible, before requesting the change to the decision agent.

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