Management and Production Engineering Review
Volume 16 • Number 2 • June 2025 • pp. 1–14
DOI: 10.24425/mper.2025.154934

Integrating QFD and Fuzzy AHP for the Analysis of Customer Needs: An Automotive Case Study

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Received: 25 October 2024
Accepted: 24 December 2024

Abstract
Understanding customer needs is a crucial task in designing a product. An improper definition of customer requirements affects the product's design, reducing the product's quality, and ultimately reducing customer satisfaction. This paper aims to address this issue by developing a QFD-FAHP model to study customer needs and select the best product that satisfies those needs. Customer requirements are identified and then evaluated using FAHP, based on customer evaluations after a survey is conducted. The technical requirements that address those requirements are then identified, and QFD is applied, building the HOQ to prioritize the technical characteristics, and the alternatives are ranked using AHP. The proposed model is validated through a case study conducted at a car manufacturing company. The findings of this study confirm and prove the efficiency of the proposed model in studying customer needs and delivering a product of quality that satisfies those needs.

Keywords
Customer requirements; Analytic Hierarchy Process; Quality Function Deployment; Fuzzy logic; Decision-making.

Introduction

In today's industrial field, it is necessary to prioritize the product's quality at every step of the manufacturing process, including early in the designing phase. To do so, customer requirements and expectations must be integrated right into the initial design of the product, since rectifying a design error in the middle of the manufacturing process is practically impossible. Approximately 70% of non-quality costs are caused by an erroneous definition and/or understanding of customer needs, leading to a poor product design (Chao & Ishii, 2005). However, in most cases, almost 75% of the total cost of production is determined in the designing phase (Molcho et al., 2014; Saravi et al., 2008). As a result, past the designing phase, cost-cutting strategies can be applied just for the remaining 25% of the total cost of production (Molcho et al., 2014; Saravi et al., 2008). In this context, the concept of "design for quality" emerged, leading to the development of many quality methods and tools over time, so that customer requirements and needs can be considered in the early stages of the production process, such as QFD (Quality Function Deployment).

The QFD method, considered one of the most important tools in the quality field, is widely used in the literature and industrial field. It is a quality method that helps develop and design products with high quality, focusing on what the customer wants. This method improves the quality of the products and services by truly understanding and identifying customer needs and requirements, and then addressing those needs by determining the right technical characteristics (Ardani et al., 2014). QFD is considered a very useful method to study customer needs and requirements, and turn them into technical characteristics of the product. However, in certain problems such as multi-criteria decision-making problems, QFD on its own is not the best approach to adopt. For this kind of problem, MCDA (Multi-Criteria Decision Analysis) methods are an interesting approach. MCDA is a decision-making based approach. It relies on decision-making methods that help decision-makers rationally determine the best solution possible, by explicitly con-

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sidering and studying all the criteria and parameters of the problem (De Felice & Petrillo, 2011). Therefore, in order to successfully apply these methods, the main parameters of the decision-making problem must first be defined, i.e. the alternatives that are available to the decision-makers, as well as the different criteria of the problem that the decision-makers will study and consider before making their decision, to identify and determine the most appropriate alternative possible.

Many MCDA methods were developed over the years, such as AHP, MULTIMOORA, MAUT, TOPSIS, VIKOR. All these MCDA methods are widely used in the various industrial fields, but most of these methods do not handle subjective data and subjective criteria in the best way possible, and they use a linear system in weighting and evaluating the criteria and alternatives (Singh & Pant, 2021; Velasquez & Hester, 2013), thus not taking into consideration potential interdependencies among the criteria, which could lead to poor judgments and inaccurate results. On the other hand, the AHP (Analytic Hierarchy Process) method, through its pairwise comparisons system, consider potential interactions between the different criteria. Furthermore, subjective data can be studied and processed in a more efficient way in AHP, through Saaty's scale. In this context, combining the QFD and AHP methods to study customer requirements and offer the best alternative to satisfy their needs, thus optimizing customer satisfaction, is an innovative approach.

The AHP method is a very effective MCDA method in studying both quantitative and qualitative criteria of MCDA problems based on the judgments and evaluations of the decision-makers. However, fuzziness and uncertainty that exist in many MCDA problems, and in human judgment in general, can lead to imprecise and inaccurate evaluations by decision-makers in the traditional AHP. The FAHP (Fuzzy Analytic Hierarchy Process) approach was introduced to address this issue. The FAHP method is an advanced MCDA method, that was developed and established based on the conventional AHP. Many studies have been conducted in the literature using FAHP by various researchers. These studies confirmed and proved the efficiency of FAHP in handling the uncertainty and imprecision of the data in MCDA problems compared to the conventional AHP. Therefore, the FAHP method was adopted in this study instead of the traditional AHP to analyze customer needs.

In this context, the present paper aims to develop a new QFD-FAHP method to study customer requirements for a car manufacturing company that intends to release a new car model to the market, and evaluate and prioritize the alternatives available to determine which of the car model designs best addresses customer needs. The weights of customer requirements in the HOQ (House Of Quality) are evaluated using FAHP. The relative and normalized weights of the technical characteristics of the HOQ are calculated using QFD. The alternatives are then evaluated and prioritized through AHP to select the best car model design. The remainder of this paper is structured in the following manner. In Section 2, a literature review of existing work and studies on the QFD, AHP, as well as QFD-AHP applications in the industrial field is presented. Section 3 presents the QFD and AHP methods. Section 4 presents and describes the proposed QFD-FAHP methodology. The proposed methodology is validated through a case study and the results are discussed in Section 5. Section 6 summarizes and concludes the contribution.

Literature review

Many QFD applications can be found in the literature, in different industrial fields. Akbar et al. (2010) applied QFD to develop dashboard products on cars. Based on the conducted survey, the HOQ that describes customer requirements and the technical characteristics for the dashboard was built. Ahmed & Amagoh (2010) aimed in their paper to increase the tempered glass demand for a SAT glass manufacturer, by applying QFD and integrating customer needs and requirements into the manufacturing process. The QFD method has also been applied in the healthcare industry (Chaplin & Terninko, 2000) and in the management of academic institutions for conducting quality education and research (Chou, 2004). Tan & Pawitra (2001) applied QFD to formulate suitable strategies, in order to address the needs of tourists. Killen et al. (2005) used QFD to translate and convert the insight and ideas of a company into actions and solutions by creating innovative strategies, thus demonstrating the application of QFD in strategic planning. Incorporating fuzzy numbers in the HOQ process to address the vagueness in people's assessments, Chan & Wu (2005) have provided a systematic approach to QFD implementation regarding fried Chinese vegetables. Bottani & Rizzi (2006) applied a fuzzy QFD approach to address the strategic issue of customer service management in logistics services. Tsang & Au (2024) applied QFD to study and understand how different smart tourism technologies could be converted into tourists' expectations of smart tourism experiences. Lalvand & Owlia (2024) developed a combination of customer clustering and QFD to improve and develop mobile services to meet customer needs and improve the performance of the organization. Furthermore, Bevilacqua et al. (2006) proposed a model of supplier selection based on a fuzzy QFD approach. These various applications prove the flexibility and utility of the QFD method in different industrial fields.

Several research studies have also been carried out in the literature using MCDA methods. MCDA methods vary significantly by their steps, their mathematical tools, how the alternatives are ranked, the type of problems they are used in, etc. Applying the same problem with the same data to two different MCDA methods does not guarantee having the same result. The MCDA method to adopt is determined depending on the problem being studied (Lin et al., 2008). If the goal is to obtain values to compare them, methods such as AHP, MAUT, and MULTIMOORA can be adopted. If the goal is to determine the most appropriate alternative from the options and solutions that are available, methods like AHP, TOPSIS, and VIKOR are more effective. There are also other methods like ELECTRE and PROMETHEE, that are based on conformity assessment and pairwise comparisons to reach the desired objective. MCDA methods have been used in various fields in the literature. Chen et al. (2020) proposed an extended MULTIMOORA methodology, using the Choquet integral and OWGA (Ordered Weighted Geometric Averaging) operator for FMEA (Failure Mode and Effects Analysis). Sennaroglu & Varlik Celebi (2018) used various MCDA methods in a location selection problem for a military airport. The goal was to identify the best location among various candidate locations available. The weights of the criteria were determined using AHP, while the ranking and selection process of the alternatives was carried out using the VIKOR and PROMETHEE methods. The results of VIKOR and PROMETHEE were then compared to the results of other MCDA methods. Results showed that the same alternative was determined as the most suitable one by all MCDA methods that were applied in the study, and that all these methods provided identical ranking and classification of the location alternatives. Furthermore, Hariri et al. (2023) published a review article analyzing and classifying various journal papers about integrating MCDA methods with the QFD method. Results showed that hybrid MCDA-QFD methods have been adopted in many fields, especially in the industrial and manufacturing fields.

As for the applications of AHP, several areas have been covered in the literature, such as maintenance selection problems (Bertolini & Bevilacqua, 2006), evaluation of innovative educational projects (Melřn et al., 2008), mobile phone selection based on its features (Işıklar & Büyüközkan, 2007), improvement of airports' passenger security checks (Yoo & Choi, 2006), ranking and classifying components and materials for control systems (Razmi et al., 2006), etc. Moreover, Benyoucef & Canbolat (2007) proposed an integrated AHP and fuzzy logic approach in an electronic devices supplier selection problem in a hospital. Kubler et al. (2016) carried out in their paper a literature review, analyzing 190 papers about applications of the FAHP method. Results showed that FAHP is mostly used in the manufacturing and industrial fields, and that 43% of the reviewed papers combined FAHP with other methods, such as TOPSIS and QFD. In addition, Salehzadeh & Ziaeian (2024) reviewed the applications of the AHP and FAHP methods in human resource management.

Many researchers have attempted to combine AHP with QFD, in order to introduce ingenuity and increase objectivity in their contributions. Paltayian et al. (2023) proposed a decision-making framework for e-banking operations, based on an integrated QFD-AHP approach. Raco et al. (2024) aimed in their study to design an online business platform, using both the QFD and AHP methods, focusing on considering customer needs. Hua Lu et al. (1994) proposed a methodology integrating AHP, QFD, and benchmarking to develop a strategic planning framework for a long-range marketing policy. Partovi (2006) applied AHP, ANP (Analytic Network Process), and QFD to determine a strategic solution to the location problem incorporating both internal and external criteria. The AHP-ANP-QFD framework has further been applied by Partovi (2007) for process selection and evaluation of manufacturing systems. Bhattacharya et al. (2005) have reported the application of the integrated AHP-QFD framework for robot selection problems to address customer requirements. Similarly, the AHP-QFD framework was applied to prioritize tooling requirements and subsequently select the most appropriate tooling process (Hanumaiah et al., 2006). Ginting & Ishak (2020) presented a literature review on AHP-QFD papers, and carried out an in-depth analysis of the benefits and drawbacks of the integrated AHP-QFD method, providing suggestions based on the analysis of the method development. De Oliveira et al. (2020) also published a review article on AHP-QFD papers, selecting and analyzing 100 academic papers from the Scopus database.

Based on the literature review above, many papers and contributions proposed an application of the QFD method and MCDA methods such as AHP, alongside fuzzy logic, in various fields and areas, including the study of customer requirements, either by using one of the mentioned methods individually or by partially integrating them to propose a new integrated approach (AHP-QFD, fuzzy AHP…). However, there are very few papers in the literature that integrate QFD with AHP and fuzzy logic to study customer needs and requirements in real case studies, particularly in the automotive industry, leaving a significant gap in the literature in this particular field. The present study aims to address this gap by proposing an integrated FAHP-QFD methodology and applying it in a car selection problem.

Theoretical methods

Quality Function Deployment

QFD is a planning process that helps the organization implement various technical support tools effectively and complement each other to prioritize each problem (Putra et al., 2023). The concept of QFD is to ensure that all the departments and parts of the organization are committed to improving the overall quality, in order to satisfy the customer's needs. This method consists, at first, of identifying what the customer wants, and then determining the technical characteristics that address customer needs and requirements. The use of QFD helps gain a significant competitive advantage, as it prioritizes the solutions that must be adopted in the company, increasing the quality of the product, and thus increasing customer satisfaction (Ginting et al., 2020). In QFD terminology, customer requirements are known as the WHATs, while the technical characteristics are referred to as the HOWs. In the QFD method, four 'matrices' or 'houses' are developed (Akao, 2004; Besterfield-Michna et al., 2002; Cohen, 1995; Govers, 1996; Guinta & Praizler, 1993; Rao, 1996):

- The HOQ, also known as the matrix of product planning
- The matrix of product deployment
- The matrix of process planning
- The matrix of production planning

The use of these matrices allows companies and organizations to design reliable products of good quality, especially the HOQ, which is considered the primary and most important tool of the QFD method. In most cases, as proved in many papers in the literature (Chou, 2004; Radharamanan & Godoy, 1996; Tan & Pawitra, 2001), the results of QFD depend almost entirely on the HOQ matrix. The HOQ is developed through the following steps (Yousefi & Hadi-Vencheh, 2010):

Step 1: The first step is to identify customer requirements (the WHATs), and clearly define and determine the customer's expectations from the product.

Step 2: The next step is to assign priorities to customer requirements, based on a determined scale.

Step 3: The technical characteristics (the HOWs) that address and satisfy the identified customer requirements are determined by a team of experts.

Step 4: The relationship matrix between the WHATs and HOWs is built. The experts' team determines which WHAT(s) has an impact on which HOW(s), and to what extent.

Step 5: The correlation matrix is developed on the top of the HOQ, or the 'roof' of the HOQ. The correlations and relationships between the HOWs are determined.

Step 6: The final step is to calculate the weights of the technical characteristics using Eq. (1):

$$w(\mathrm{HOW}_j) = \sum_{i=1}^{m} a_{ij} w(\mathrm{WHAT}_i) \tag{1}$$

where $w(\mathrm{HOW}_j)$ is the weight of the j^{th} technical characteristic, a_{ij} is the value that represents the relationship and correlation between the i^{th} customer requirement and the j^{th} technical characteristic, $w(\mathrm{WHAT}_i)$ is the weight or priority of the i^{th} customer requirement, and m is the number of customer requirements. The technical characteristic with the highest weight is considered the most important one, and should be allocated the most resources by the organization. Figure 1 represents the structure of the HOQ.

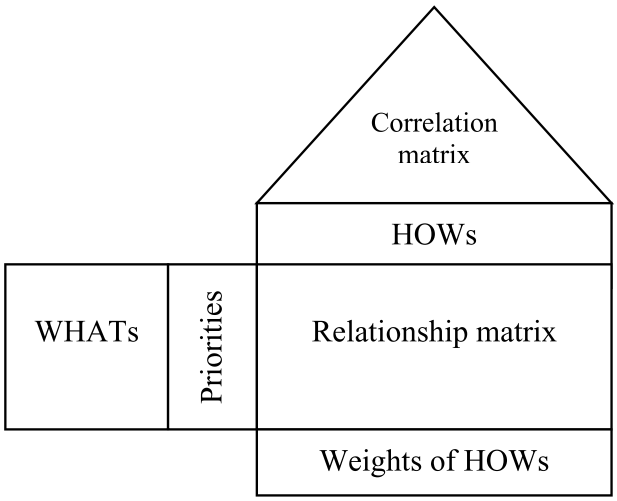

Fig. 1. Structure of the HOQ

Analytic Hierarchy Process

The AHP method was developed by Saaty in 1978. It is an MCDA method that helps deal with complex decision-making problems that are based on multiple criteria, by decomposing the problem and structuring it hierarchically into multiple levels, and then studying each of those levels separately (Saaty, 2001, 2006). The resultant hierarchical structure is shown in Figure 2. The top level represents the goal or the objective of the study. The second level describes the criteria. These criteria can be divided into sub-criteria, and represented in the next level of the hierarchy, depending on the problem. Meanwhile, the alternatives considered for the problem are represented in the last level (Hajeeh, 2010). The principle of AHP is to make pairwise comparisons to determine the weight and importance of each variable (criteria, sub-criteria, and alternatives) at each level of the hierarchy, thus evaluating all the alternatives and making the best decision possible among the available alternatives (De Felice & Petrillo, 2012; Semih & Seyhan, 2011).

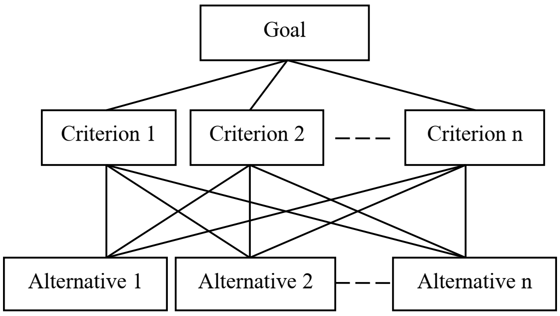

Fig. 2. Hierarchical structure of an AHP problem

The AHP method is carried out through the following steps (Zaizoune & Herrou, 2023):

Step 1: The first step is to evaluate the criteria through pairwise comparisons. The decision-makers, who are either the customers or the experts, depending on the problem being studied, evaluate the importance of each criterion, by making pairwise comparisons between all the criteria, using the linguistic scale: *"Equally important, Slightly more important, More important, Strongly more important, Extremely important"*. These evaluations are converted into numeral notes using Saaty's scale in Table 1, generating the pairwise comparison matrix $\mathbf{C} = [c_{ij}]_{nxn}$, where n is the number of criteria, c_{ij} is the relative importance of criterion i over criterion j, and its reciprocal, $1/c_{ij}$, is equal to the relative importance of criterion j over criterion i, c_{ji} (Zaizoune & Herrou, 2023).

$$\mathbf{C} = [c_{ij}]_{nxn} = \begin{bmatrix} 1 & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix}$$

It is important to note here that in most cases, more than one decision-maker evaluates the criteria and makes pairwise comparisons between them, therefore multiple pairwise comparison matrices are obtained. These matrices are aggregated to obtain one collective pairwise comparison matrix. This can be achieved simply by determining the arithmetic mean of each element of the matrix.

Table 1
Saaty's scale

Note	Importance
1	Equally important
3	Slightly more important
5	More important
7	Strongly more important
9	Extremely important
2, 4, 6, 8	Intermediate judgment values

Step 2: The consistency of the obtained comparison matrix is examined. In some cases, it is possible to find a conflict or contradiction in the evaluations in the comparison matrix. For example, if a decision-maker's evaluations for criteria 1, 2 and 3 are $c_{12} = 5$ and $c_{13} = 1$, then the logical conclusion would be that $c_{23} = 1/5$ ($c_{32} = 5$). However, if the same decision-maker's evaluations state for instance that $c_{23} = 3$, then the evaluations between the criteria 1, 2 and 3 would be conflicting. Therefore it is important to check the consistency of the comparison matrix, even though it is overlooked by some researchers, as the weights of the criteria can still be determined without this step.

The consistency of the matrix can be examined by calculating the consistency ratio CR using Eq. (2), where CI is the consistency index, and RI is the random index (Saaty, 2000):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{3}$$

CI may be determined using Eq. (3) (where n represents the number of criteria, and $\lambda_{\max}$ represents the principal Eigen value of the matrix), and RI can be determined based on Saaty's table shown in Table 2.

Table 2
Random index value by Saaty

n	3	4	5	6	7	8	9	10	11
RI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

The comparison matrix is consistent if CR < 0.1. If not, the evaluations and pairwise comparisons of the decision-makers need revision, and the comparison matrix must be rebuilt.

Step 3: In this step, the criteria are ranked and prioritized. The pairwise comparison matrix must first be normalized, by dividing the value of each element c_{ij} in the matrix by the sum of the elements of column j. Based on this normalized matrix, the relative weight w_i of criterion i can be determined, by calculating the arithmetic mean of the values in row i in the normalized matrix.

Step 4: The final step of AHP is to classify and rank the alternatives, by applying the same steps described above, except for one difference: the alternatives are compared pairwise for each criterion. As a result, a total of n pairwise comparison matrices will be obtained, one for each criterion. The output of each matrix is the vector of relative preference indexes p_i^k of the alternatives for criterion k. Based on the results of each matrix, the preference index p_i of each alternative can be determined using Eq. (4), which allows the classification of the alternatives.

$$p_i = \sum_{k=1}^{n} p_i^k w_k \tag{4}$$

Fuzzy Analytic Hierarchy Process

Various FAHP studies and applications have been proposed in the literature by many researchers. Chang et al. (2003) aimed in their paper to develop a methodology that allows them to evaluate airport performances. The authors applied the gray statistics method in order to select the criteria, and they ranked and prioritized those criteria by calculating their weights using FAHP. And finally, to rank the airports by performance, they used a fuzzy synthetic evaluation and TOPSIS approach.

Mosase et al. (2017) aimed in their paper to compare the accuracy of the AHP and FAHP methods in a problem of determination of the suitable location of rain water harvesting in Botswana. The authors came to the conclusion that AHP, despite being widely used in the decision-making and analysis field, cannot handle the uncertainties and imprecision of the criteria like FAHP does.

The steps of the FAHP process are practically identical to those described above, excluding 3 differences (Zaizoune & Herrou, 2023):

- *1st difference:* In order to deal with the fuzziness and uncertainty of the data and human judgment, the linguistic variables are converted into TFNs (Triangular Fuzzy Number) instead of crisp exact values. The use of TFNs and fuzzy logic makes the judgments and evaluations of the decision-makers more accurate and precise, increasing the overall accuracy of the study.
- *2nd difference:* The pairwise comparison matrix is established by converting the linguistic evaluations into numeral notes. The scale used to accomplish this conversion in FAHP is different than the one used in AHP, with TFNs instead of crisp values. The Saaty's scale with TFNs is represented in Table 3.

Table 3
Saaty's scale with TFNs

Fuzzy note	Importance
(1,1,1)	Equally important
(2,3,4)	Slightly more important
(4,5,6)	More important
(6,7,8)	Strongly more important
(9,9,9)	Extremely important
(1,2,3), (3,4,5), (5,6,7), (7,8,9)	Intermediate judgment values

- *3rd difference:* The weights of the alternatives and criteria are obtained in fuzzy representation: $\hat{w}_i = (l_i, m_i, h_i)$. Therefore they need to be defuzzified to obtain the crisp exact weights, using Eq. (5).

$$w_i = \frac{l_i + m_i + h_i}{3} \tag{5}$$

Proposed methodology

The proposed FAHP-QFD methodology is structured around three main steps. First, customer requirements, often expressed in vague linguistic terms by the customer, are ranked using FAHP. QFD is then applied to determine the technical characteristics as well as their weights. Based on these weights, the alternatives are ranked and prioritized using AHP, and the most suitable car model is selected. A simple AHP approach is used in ranking the alternatives, since the evaluations of the experts are assumed to be more precise, making additional fuzzy processing unnecessary.

In the QFD method, determining the importance of each customer requirement is a crucial step to define the right technical characteristics as well as their importance, in order to identify which of these technical characteristics should be allocated the most resources by the company. Customer requirements are ranked in the literature by different methods, such as direct rating methods, which consists of directly asking customers to rate and evaluate each requirement, based on a predefined scale. Other customer requirements ranking methods include the integration of the Kano model, and integrating direct ratings and survey results with statistical analysis techniques. However, in most cases, determining the importance of customer requirements using these methods may not be very precise, and may not reflect entirely the customer's needs and the importance of each requirement in the eyes of the customer. To resolve this issue, the FAHP method is used in this study to determine the importance of customer requirements, based on customer evaluations, in their own linguistic terms. Combining the pairwise comparisons of AHP with fuzzy logic, which converts linguistic variables into precise numeral values, proves to be extremely effective in this case. Furthermore, AHP is applied at the end of the study to evaluate and rank the alternatives, in order to identify the one that best satisfies customer needs. AHP was used instead of FAHP in ranking and prioritizing the alternatives, since unlike the study of customer requirements, which is based on fuzzy and vague customer evaluations and judgments, the study and ranking of the alternatives are based on the exact numeral results of QFD and the HOQ, and the evaluations and judgments of the experts, that are less fuzzy and uncertain, and that do not require the use of fuzzy logic and FAHP. Therefore, a simple AHP approach is adopted in ranking the alternatives rather than FAHP.

In this context, the QFD-FAHP approach is adopted in this paper to study customer requirements and determine the best solution to satisfy customer needs. The proposed methodology is represented in Figure 3.

The first step of the proposed methodology is to determine customer needs and requirements, and clearly identify what the customer wants and expects from the product or service. Once the requirements are identi-

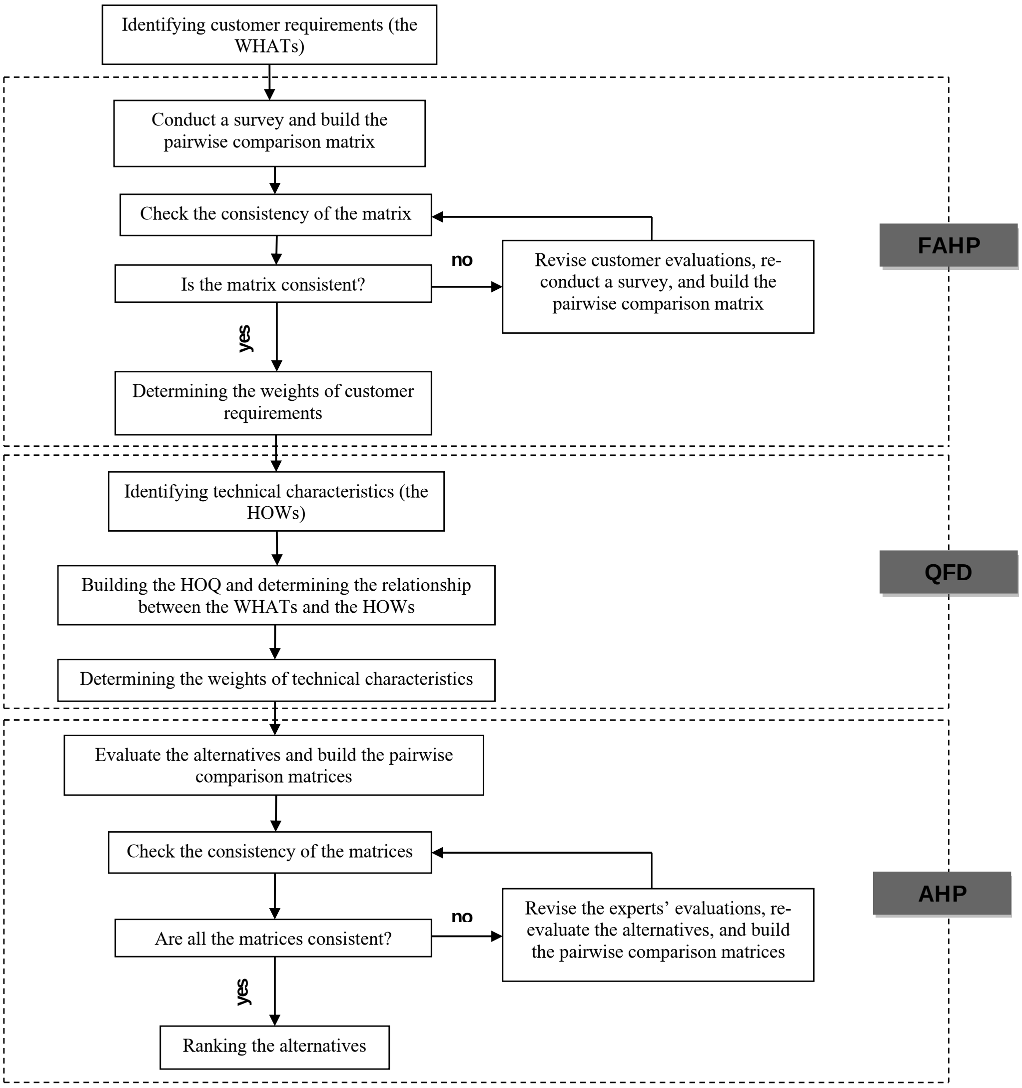

Fig. 3. The proposed QFD-FAHP methodology

fied, the weight of each requirement is determined using FAHP. To do so, a survey is conducted alongside a certain number of customers, in which they make pairwise comparisons between the requirements, and evaluate the importance of each requirement compared to the other requirements. These evaluations are then converted into fuzzy notes, and the pairwise comparison matrix is built, which needs to be checked if it is consistent or not, as explained in Section 3. If the matrix is not consistent, customer evaluations need revision, the survey is re-conducted, and the correspondent comparison matrix is built. If it is consistent, FAHP is used to determine the weights of customer requirements.

Once customer requirements are evaluated and prioritized, the next step is to determine the technical characteristics that address the identified requirements. QFD is then used to build the HOQ and determine the relationship between each characteristic and each requirement, and ultimately calculate the relative importance of the technical characteristics. The final step of the proposed methodology is to rank and prioritize the alternatives. AHP is used to make pairwise comparisons between the alternatives and build a pairwise comparison matrix for each technical requirement. The consistency of the matrices is then checked. If a matrix is not consistent, the experts need to revise their evaluations and build the new matrix. If all the matrices are consistent, the weights of the alternatives are calculated using AHP, and the alternatives are finally ranked and prioritized, determining the best and most suitable alternative.

Case study

The goal of the present study is to analyze customer requirements for a car manufacturing company that intends to release a new model to the market and evaluate and prioritize the alternatives available to determine which of the car model designs best addresses customer needs. The study is carried out through the steps described in the proposed methodology section.

Identifying customer requirements (the WHATs)

In this study, 5 customer requirements that represent the main characteristics of a car were considered:

- Affordable price (CR1)
- Safety (CR2)
- Reliability (CR3)
- Low fuel consumption (CR4)
- Comfort (CR5)

Determining the weights of customer requirements

The weights of customer requirements are calculated using FAHP to prioritize them and determine their relative importance. To do so, and in order to truly determine the importance of each requirement in the eyes of the customer, a survey was conducted, asking a total of 50 customers to make a pairwise comparison of all the requirements, using the linguistic scale: *"Equally important, Slightly more important, More important, Strongly more important, Extremely important"*.

After converting the results of the survey to fuzzy notes using Saaty's scale in Table 3, and aggregating the matrices of all the customers, the collective fuzzy pairwise comparison matrix in Table 4 was established. However, before moving on to determining the weights of customer requirements, the obtained matrix's consistency needs to be checked.

In this study, the number of parameters is $n = 5$ (5 customer requirements, 5 criteria). Thus, based on Table 2, RI = 1.12.

The Eigen value $\lambda_{\max}$ of the comparison matrix is $\lambda_{\max} = 5.417$. As a result, the consistency index can be determined using Eq. (3):

$\mathrm{CI} = \dfrac{5.417 - 5}{5 - 1} = 0.10425$. The consistency ratio can now be determined using Eq. (2):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{0.10425}{1.12} = 0.093.$$

Table 4
Fuzzy pairwise comparison matrix

	CR1			**CR2**			**CR3**			**CR4**			**CR5**		
CR1	1	1	1	1	1	1.5	1.1	1.3	1.4	3.6	5.6	7.7	4.4	6.9	9
CR2	0.8	0.7	0.68	1	1	1	0.6	0.8	0.9	1.6	1.7	1.7	3	5.5	7.7
CR3	0.89	0.8	0.71	2	1	1.1	1	1	1	2	2.9	3.5	4.5	6.5	8.6
CR4	0.28	0.2	0.13	1	1	0.6	0.5	0.4	0.3	1	1	1	1.5	2.4	3.1
CR5	0.23	0.1	0.11	0	0	0.1	0.2	0.2	0.1	0.7	0.4	0.3	1	1	1

Since CR < 0.1, the fuzzy pairwise comparison matrix can be considered consistent, and can be normalized. The obtained normalized fuzzy pairwise comparison matrix is shown in Table 5.

The fuzzy weight $\hat{w}_k$ of each requirement is calculated and then defuzzified using Eq. (5). The results are shown in Table 6. Results show that the most important requirement for the customers is the price of the car, followed by its reliability and its safety. Inversely, the comfort of the car is not considered an important need for the customers compared to the other requirements.

Identifying technical characteristics (the HOWs)

In order to determine the technical characteristics that would address customer requirements, a review of the automotive industry literature was conducted, and various experts in the automotive industry were contacted and asked to contribute to this study. After reviewing the literature and solutions proposed by the experts, the following technical characteristics were considered:

1. Engine type (petrol, diesel, electric…) (TC1)
2. Weight (TC2)
3. Type of transmission (TC3)
4. Engine power (TC4)
5. Cost of raw material (TC5)

Building the HOQ and determining the relationship between the WHATs and the HOWs

Building the HOQ requires establishing the relationship matrix. To do so, the correlations and relationship between the WHATs and HOWs must be determined. Three types of relationships were considered: Strong (9), Medium (3), and Weak (1). The relationship matrix is shown in Figure 4.

	HOWs				
WHATs	Engine type	Weight	Type of transmission	Engine power	Cost of raw material
Affordable price	9		3	3	9
Safety		9			9
Reliability	3	1	1		9
Low fuel consumption	9	3	3	9	3
Comfort			3		3

Fig. 4. Relationship matrix

The values in the matrix represent to what extent a technical characteristic addresses and affects a customer requirement. For example, a car with an electric engine does not have the same price as one with a diesel engine. Therefore the engine type has a strong cor-

Table 5
Normalized fuzzy pairwise comparison matrix

	CR1			CR2			CR3			CR4			CR5		
CR1	0.31	0.4	0.38	0.3	0	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.3	0.3	0.3
CR2	0.25	0.3	0.26	0.2	0	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2	0.3
CR3	0.28	0.3	0.27	0.3	0	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3
CR4	0.09	0.1	0.05	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CR5	0.07	0.1	0.04	0.1	0	0	0.1	0	0	0.1	0	0	0.1	0	0

Table 6
Weights of customer requirements

Customer requirement	Fuzzy weight $\hat{w}_k$	Defuzzified weight w_k	Rank/Priority
Affordable price	(0.326, 0.361, 0.379)	0.356 (35.6%)	1
Safety	(0.204, 0.217, 0.221)	0.215 (21.5%)	3
Reliability	(0.287, 0.277, 0.274)	0.279 (27.9%)	2
Low fuel consumption	(0.112, 0.102, 0.094)	0.103 (10.3%)	4
Comfort	(0.069, 0.042, 0.031)	0.047 (4.7%)	5

		HOWs				
WHATs	Relative importance of WHATs	Engine type	Weight	Type of transmission	Engine power	Cost of raw material
Affordable price	0.356	9		3	3	9
Safety	0.215		9			9
Reliability	0.279	3	1	1		9
Low fuel consumption	0.103	9	3	3	9	3
Comfort	0.047			3		3
Weight of HOWs		4.968	2.523	1.797	1.995	8.1
Relative weight of HOWs		0.256	0.13	0.093	0.103	0.418

Fig. 5. Final HOQ

relation with the price of the car. The cost of raw material has either a strong or medium correlation with all customer requirements. This is due to the fact that the quality of raw material will have an impact on all aspects of the final product, like the safety of the car and its reliability, which makes the cost of raw material an important characteristic for the company that affects all customer requirements.

Determining the weights of technical characteristics

The weights of the technical characteristics can be calculated based on the relationship matrix in Figure 4, using Eq. (4). The results are shown in Table 7.

Table 7
Weights of technical characteristics

Technical characteristic	Weight	Rank/priority
Engine type	4.968	2
Weight	2.523	3
Type of transmission	1.797	5
Engine power	1.995	4
Cost of raw material	8.1	1

Results show that the most important technical characteristic is the cost of raw material, followed by the engine type. This is due to the strong relationship between the cost of raw material and the price of the car, which is considered by the majority of customers the most important requirement and factor for buying a car.

Based on these results, relative weights of the technical characteristics can be calculated, thus establishing the final HOQ, represented in Figure 5.

Ranking the alternatives

Now that the weights and importance of the technical requirements are determined, the final step is to evaluate and rank the alternatives, which are the car model designs available. The alternatives are evaluated for each technical characteristic, thus 5 pairwise comparison matrices will be obtained. The experts evaluate and make pairwise comparisons between the alternatives for each characteristic. Based on these evaluations and Saaty's scale in Table 1, a pairwise comparison matrix is generated for each characteristic. Results are shown in Tables 8, 9, 10, 11, and 12, respectively for each characteristic.

Based on these results, and using Eq. (4), the preference index p_i of each alternative can be calculated, and the alternatives can be ranked and prioritized. The results are shown in Table 13.

Based on the results in Table 13, and based on the QFD-FAHP study that was conducted in this paper, the car model design that best satisfies customer needs is the model A1, followed by A6, A5, A3, A4, and finally A2. And according to results in

Table 8
Pairwise comparison matrix for TC1

TC1	A1	A2	A3	A4	A5	A6	Index $\mathbf{p_i^1}$
A1	1	5	3	1	3	3	0.296
A2	0.2	1	3	0.333	3	0.333	0.110
A3	0.333	0.333	1	0.333	1	0.2	0.064
A4	1	3	3	1	5	3	0.291
A5	0.333	0.333	1	0.2	1	0.333	0.060
A6	0.333	3	5	0.333	3	1	0.179

CR = 0.083 < 0.1, the matrix is consistent.

Table 9
Pairwise comparison matrix for TC2

TC2	A1	A2	A3	A4	A5	A6	Index p_i^2
A1	1	5	3	1	3	1	0.264
A2	0.2	1	3	0.333	1	0.333	0.102
A3	0.333	0.333	1	1	1	0.333	0.089
A4	1	3	1	1	3	0.333	0.193
A5	0.333	1	1	0.333	1	0.333	0.075
A6	1	3	3	3	3	1	0.286

CR = 0.084 < 0.1, the matrix is consistent.

Table 10
Pairwise comparison matrix for TC3

TC3	A1	A2	A3	A4	A5	A6	Index p_i^3
A1	1	3	1	1	3	1	0.215
A2	0.333	1	1	1	0.333	0.333	0.091
A3	1	1	1	1	1	0.333	0.124
A4	1	1	1	1	3	0.333	0.154
A5	0.333	3	1	0.333	1	0.333	0.113
A6	1	3	3	3	3	1	0.302

CR = 0.08 < 0.1, the matrix is consistent.

Table 11
Pairwise comparison matrix for TC4

TC4	A1	A2	A3	A4	A5	A6	Index p_i^4
A1	1	3	3	3	3	0.333	0.224
A2	0.333	1	0.333	3	0.333	0.2	0.075
A3	0.333	3	1	3	0.333	0.333	0.116
A4	0.333	0.333	0.333	1	0.333	0.2	0.049
A5	0.333	3	3	3	1	0.333	0.169
A6	3	5	5	5	3	1	0.373

CR = 0.089 < 0.1, the matrix is consistent.

Tables 8, 9, 10, 11, and 12, the model A1 has a higher relative importance than the other models for most of the technical characteristics, especially for the characteristics "engine type" and "weight", which are ranked as one of the most important technical characteristics in Table 7. As for the most important characteristic, "cost of raw material", the model A1 still has a higher relative importance than most of the other models. And based on the relationship matrix in Figure 4, the characteristics "engine type" and "weight" have a strong correlation with the requirements "affordable price" and "low fuel consumption", and the requirement "safety" respectively. This implies that

Table 12
Pairwise comparison matrix for TC5

TC5	A1	A2	A3	A4	A5	A6	Index p_i^5
A1	1	3	0.333	3	0.333	3	0.169
A2	0.333	1	0.333	3	0.333	0.333	0.089
A3	3	3	1	3	1	3	0.278
A4	0.333	0.333	0.333	1	0.333	0.333	0.060
A5	3	3	1	3	1	3	0.278
A6	0.333	3	0.333	3	0.333	1	0.125

CR = 0.093 < 0.1, the matrix is consistent.

Table 13
Priorities of the alternatives

Alternative i	Preference index p_i	Rank
A1	0.224	**1**
A2	0.095	**6**
A3	0.167	**4**
A4	0.144	**5**
A5	0.169	**3**
A6	0.201	**2**

the model A1 has an affordable price, and therefore satisfies the most important requirement for the customer, and has a high level of safety, which is also considered an important requirement by the customer.

In summary, and based on the analysis above, the car model A1 satisfies the most important customer requirements, and is therefore considered as a product of good quality. Thus, the model A1 is selected and is given priority to be launched in the market.

Conclusion

Determining customer needs and requirements in a product with precision, and deciding how to address them is a crucial step to achieve good quality and customer satisfaction. This involves a proper evaluation of customer requirements, the identification of technical characteristics, which requires accurate decision-making, etc. This paper attempted to prove the effectiveness of the proposed QFD-FAHP methodology in this context, in a car selection problem.

In this study, FAHP is applied to evaluate and measure the importance of each customer requirement, based on customer evaluations, increasing the accuracy and precision of the data and the overall study. QFD is used to identify the technical characteristics that address customer requirements, determine the relationship between the technical characteristics and customer requirements in the HOQ, and evaluate and prioritize the technical requirements, whereas AHP is used to evaluate and rank the alternatives.

The use of AHP and fuzzy logic is extremely effective in analyzing the data of the study with precision and accuracy. However, it does not completely eliminate subjectivity. The proposed methodology highly relies on the subjective judgments and evaluations of the customers, which constitutes a limitation of this study. Moreover, the pairwise comparisons of AHP can prove to be very time-consuming, especially if they have to be reviewed and revised if the comparison matrix is inconsistent, which could constitute an inconvenience in terms of cost and time, particularly in larger-scale problems and applications with a high number of parameters.

Future studies could focus on expanding the car selection problem to include more parameters, by considering more customer requirements and alternatives. In the present study, only 5 customer requirements were considered, since they are the most demanded features and requirements from the customer. Adding more requirements, and thus more technical characteristics to address them, could enhance and validate the credibility and relevance of the methodology, and provide a more comprehensive analysis. Future studies could also include applying the proposed methodology to study customer needs and requirements in other industrial fields.

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