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Multicriteria Decision Making: A Case Study in the Automobile Industry *

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Abstract

Multi-criteria decision analysis (MCDA) has been one of the fastest-growing areas of operations research during the last decades. The academic attention devoted to MCDA motivated the development of a great variety of approaches and methods within the field. These methods distinguish themselves in terms of procedures, theoretical assumptions and type of decision addressed. This diversity poses challenges to the process of selecting the most suited method for a specific real-world decision problem. In this paper we present a case study in a real-world decision problem arising in the painting sector of an automobile plant. We tackle the problem by resorting to the well-known AHP method and to the MCDA method proposed by Pereira and Fontes (2012) (MMASSI). By relying on two, rather than one, MCDA methods we expect to improve the confidence and robustness of the obtained results. The contributions of this paper are twofold: first, we intend to investigate the contrasts and similarities of the results obtained by distinct MCDA approaches (AHP and MMASSI); secondly, we expect to enrich the literature of the field with a real-world MCDA case study on a complex decision making problem since there is a paucity of applied research work addressing real decision problems faced by organizations.

Keywords: *AHP, Decision Making, Multicriteria Decision Analysis, Multicriteria Methodology, Automobile Industry.*

1 Introduction

In recent years, the increasing competitiveness of the global market, as well as the burst of the so-called *Global Financial Crisis*, forced companies to rethink their processes so as to rise the levels of efficiency, responsiveness and flexibility. In such contexts, resorting to MCDA to assist in strategic decision problems can turn out to be a decisive step towards achieving these goals.

*A shorter version of this paper is going to be presented at ISORAP 2013.

MCDA is a formal quantitative approach, which purpose is to aid the decision making process, by fostering in decision makers (DM) the development of a structured thinking about the decision problem at hand. The main motivation behind the development of this research field is strongly related to the recognition that human judgments can be limited, distorted and prone to bias, especially when faced with problems that require the processing and analysis of large amounts of complex information (Dodgson et al., 2000). By being aware of such hindrances, in the 60's researchers started to devote themselves to the development of MCDA methods and techniques in an attempt to overcome the limitations posed by human judgment. Due to its relevance, MCDA quickly evolved and established itself as an active research field in the 70's. The proposed methods aimed at providing guidance for carrying a structured, transparent and efficient decision making process that covers all the important factors that are likely to differentiate alternative courses of action. Besides, the application of MCDA in real-world problems helps increase the confidence of the decision makers in their decisions, by helping them reach a solution that complies with their preferences and system of values. Due to the interactive and iterative nature of MCDA process, the application of such techniques to real-world scenarios may prove to be a daunting and time consuming task, which requires a significant endeavor from both analysts (or facilitators) and decision makers. Therefore, MCDA is more suitable for supporting problems of high complexity and that may possibly lead to long term impacts (Brito et al., 2010). In this paper, we adopt the definitions of *decision makers* and *analysts* proposed by Belton and Stewart (2002), thus regarding the *decision maker* as the one who has the responsibility for the decision, and the *analysts* as those who guide and aid the decision makers in the process of reaching a satisfactory decision.

MCDA is a problem solving methodology that organizes and synthesizes the information regarding a given decision problem in a way that provides the decision maker with a coherent overall view of the problem. MCDA methods assist DM in the process of identifying the most preferred action(s), from a set of possible alternative actions (explicitly or implicitly defined), when there are multiple, complex, incommensurable and often conflicting objectives (e.g. maximize quality and minimize costs), measured in terms of different evaluation criteria. The alternative actions (also referred to as options) distinguish themselves by the extent to which they achieve the objectives and none of these alternatives will be the best at achieving all objectives (Dodgson et al., 2000). Depending on the typology of the MCDA problem at hand, these alternatives can be implicitly found by solving a mathematical model or they can instead be explicitly known (Lu et al., 2007). Criteria (also referred to as *attributes* or *objectives*) are performance measures (qualitative or quantitative) that are ranked by the DM, in terms of their perceived importance, and considered together when appraising the alternatives. By explicitly assessing the performance of different alternative actions, based on the integration of objective measurement with subjective value judgment, MCDA techniques unavoidably lead to more efficient and more informed decisions. The goal of MCDA is not to prescribe the "best" decision to be chosen but to help decision makers select a single alternative, or a short-list of good alternatives, that best fit their needs and is coherent with their preferences and general understanding of the problem (Brito et al., 2010). Usually, this alternative corresponds to the best compromise solution rather than to an optimal solution. This is somehow related to the significant degree of subjectivity inherent to any decision process and the need to incorporate this subjectivity in the assessment of the possible solutions (Lu et al., 2007).

In current days, most of the decisions are taken by a group of decision makers (GDM, also referred to as *committee*), rather than by a single individual. As stated by Zionts (1979), the idea of an omniscient decision maker is often a myth, because very seldom the DM knows the right course of action before getting acquainted with key information provided by subordinates. However, solving decision problems that involve multiple decision makers poses additional problems to the already challenging MCDA field. The difficulty of group decision making arises from the fact that GDM is comprised of individuals with different value systems and distinct perceptions of how a problem should be tackled and solved. Several procedures were proposed to aggregate the individual judgments and viewpoints of a a set of DM, regarding the attractiveness of potential alternatives, into a collective value. Forman and Peniwati (1998) argued that the two most useful procedures to address this problem are the following (Forman and Peniwati, 1998): the first procedure, known as the *aggregation of individual judgments*, assumes the group acts together as an unit, thus engaging in discussion until a consensus is achieved; on the other hand, the second procedure, referred to as *aggregation of individual priorities*, assumes the group acts as separate individuals, each one expressing their own preferences. In the latter, the collective preference can be identified using vote-counting schemes (e.g. plurality method, Hare voting, Coombs voting), ranking systems and the method of analysis of individual priorities, just to name a few.

The views of academics, such as Belton and Stewart (2002), Seydel (2006) and Dooley et al. (2009), agree that MCDA prompts learning and a better understanding of the perspectives of the DM themselves and the perspectives of the remaining key players involved in the decision process. Learning and understanding of the problem is mostly achieved by stimulating reflection, sharing of ideas and discussion about the problem at hand. This unavoidably leads to an increase of the transparency of the decision making process and might hasten the reaching of consensus. Thus, MCDA can act as a method to document, support and justify decisions.

Both the academic attention devoted to the field of MCDA and the widespread application of its methods in real-world decision problems, is a reflection of the prominence and advantages of MCDA approaches in aiding and supporting decision making.

Bearing this in mind, in this work it is our aim to present a case study on a real-world decision problem arising in the painting sector of one of Toyota's plants, using the well-known AHP method (Saaty, 1986, 1990) and the MCDA method proposed by Pereira and Fontes (2012) (henceforth, MMASSI).

The contributions of this paper are twofold: first, we intend to investigate the contrasts and similarities of the results obtained by distinct MCDA approaches (AHP and MMASSI) and discuss their suitability for solving the problem at hand; secondly, we expect to enrich the literature of the field with a real-world MCDA application on a complex decision-making problem since, according to Roy (1999) and Dooley et al. (2009), there is a paucity of applied research work addressing real decision problems faced by organizations. On a different level, it is also our purpose to encourage the adoption of a more structured thinking in problem solving on the part of decision makers of this specific company, since their decisions have been mostly taken on the basis of intuition and business experience. By embedding the principles of the scientific method into the decision-making process, decision makers will be able to work through the problem in a more structured way, improving the objectivity and transparency of the decision process, as well as their commitment to the decision. Nonetheless, it should be noted that the main motivation behind this study was not to interfere in the policies and practices of the company, as it would be if an action research scheme was adopted but, in turn, to stimulate reflection and present new ways to tackle decision problems.

The remainder of this document is organized as follows. Section 2 describes the steps involved in the deployment process of MCDA. The following section focus on explaining the foundations of the MCDA methods that will be subjected to further comparison, namely AHP and MMASSI. In Section 4, we present and detail the application of these methods to a real-world decision-making problem regarding the painting sector of one of Toyota's plants. Section 5 summarizes the paper and offers some concluding remarks.

2 MCDA Process

The deployment of MCDA is a non-linear recursive process comprised of several stages. The number of stages varies according to the adopted MCDA approach, since each one has its own idiosyncrasies. Nevertheless, it is possible to outline the critical steps of a generic MCDA process that traverse the great majority of MCDA approaches.

Usually, the first step towards the application of MCDA in real-world problems is related to both the establishment of a common understanding of the decision context and the identification of the decision problem. This step involves the decision makers and other key players that are able to make significant contributions to the MCDA process through the sharing of their expertise (Dodgson et al., 2000; Dooley et al., 2009). The shared perception of the decision context is acquired by means of the understanding of the objectives of the decision making body and the identification of not only the set of people that are responsible for the decision but also those that are likely to be affected by the decision (Dodgson et al., 2000). The second and third steps of the process comprise the identification of both the alternatives and the decision criteria that are relevant for appraising these possible courses of action. According to Dooley et al. (2009), these initial three steps are usually the most time-consuming tasks of a MCDA process, especially due to their qualitative nature. The step that follows is the assignment of relative importance weights to the chosen criteria. These weights can be determined *directly* (e.g. rating, ranking, swing, trade-off) or *indirectly* (e.g. centrality, regression and interactive). Afterwards, the DM is asked to allot a subjective score, reflecting his/her opinions, to each one of the identified alternatives according to the criteria deemed important. These scores reflect the judgment of the DM in terms of the contribution of each alternative to each performance criterion. The information thus obtained is typically organized into the so-called *performance matrix* (also referred to as *consequence matrix*, *options matrix*, or simply *decision table*), where the rows and columns correspond to the alternatives and the criteria, respectively, and each entry represents the performance of each alternative against each criterion. The following step of the process involves the summarization of the information comprised in the performance matrix into a set of multi-criteria scores, one for each possible course of action. Usually, this is achieved by aggregating (implicitly or explicitly) the subjective scores of the matrix so as to derive an overall assessment of each alternative that allows their further comparison. Based on these overall scores the set of alternatives is ranked. Eventually, the process may also involve a *sensitivity analysis* of the results to changes in scores or criteria, in order to infer on the robustness of the outcome of MCDA. Finally, the evaluation and trade-offs involved on the considered alternatives are provided to and discussed with the DM. In most cases, the final decision taken by the DM does not correspond to the top-ranked alternative, since they tend to be more concerned with the process of understanding the impact of each criterion in the ranking of alternatives than in the accuracy of the ranking (Dooley et al., 2009). Moreover, it is important to note that the results yielded by a MCDA process are not prone to generalizations, in the sense that they only apply to the set of alternatives that were evaluated (Dooley et al., 2009).

3 MCDA methods

Although several methods have been proposed over the years, here we only describe the AHP and MMASSI, since these are the ones used in our study.

3.1 Multi-attribute VS Multi-objective Decision Making

Multi-Criteria Decision Making (MCDM) problems can be broadly classified into two main categories: *Multi-attribute Decision Making* (MADM) and *Multi-objective Decision Making* (MODM). They distinguish themselves by the domain of alternatives. Therefore, while the former focuses on problems with discrete decision spaces, where there is a limited number of predetermined alternatives, the latter is applied to problems where the decision space is continuous. These continuous spaces are typically generated automatically by mathematical programming where several objective functions are defined. *Multi-objective Linear Programming* (MOLP) plays an important role on the description of these kind of problems, since it is able to translate the goals of the DM into a set of linear objective functions that are to be maximized (or minimized) subject to a set of linear constraints (Lu et al., 2007). Typically, in MADM problems the alternatives are usually described by a set of qualitative criteria, whereas in MODM problems the alternatives are appraised based on a set of quantitative criteria.

In this paper, we will focus on a MADM problem since the decision problem at hand comprises a set of discrete and limited number of alternatives.

3.2 Dominant Schools of Thought in MCDA

There are two major schools of thought in MCDA that govern the methods proposed in this field: the French school, represented by the *ELimination and (Et) Choice Translating REality* (ELECTRE) family of outranking methods (Roy, 1991); and the American school represented by the Analytical Hierarchy Process (AHP), proposed by Saaty in the 80's (Saaty, 1986, 1990). These dominant schools share the same goal since both are concerned with the problem of assessing a finite set of alternatives, based on a finite set of conflicting criteria, by a decision making body. However, they differ in the way they approach the decision problem. According to Lootsma (1990), methods arising from the French school "model subjective human judgment via partial systems of binary outranking relations between the alternatives and via a global system of outranking relations" (Lootsma, 1990), while methods from the American school build "partial value functions on the set of alternatives as well as a global value function" (Lootsma, 1990). Analogous distinctions can be made at lower levels of the taxonomy of MCDA methods since even methods within the same school distinguish themselves in terms of procedures and theoretical assumptions. These peculiarities are something one should bear in mind when selecting the most suited MCDA approach to a specific decision problem, due to the lack of consistency of the obtained results. In other words, the application of different methods to the same decision problem does not guarantee that the results yielded by each method will be the same. Hanne (1999) pointed out three important aspects that should be taken into account when selecting a MCDA method in a real-world decision context, namely: characteristics of the problem at hand, the method requirements and the DM requirements. The characteristics of the problem are related to the categories in which a given MCDM problem falls. In other words, if the problem has a continuous set of alternatives, it can be framed as a MODM, whilst if the decision space is discrete, the problem falls within the category of MADM. The proper identification of the nature of a given decision problem is of utter importance, since some MCDA methods are only able to handle one of the mentioned types (e.g. interactive approaches were devised to solve MODM problems whereas AHP, or outranking approaches, are only able to deal with MADM). Other problem types can be found both in real life and in the literature. Examples include problems with discrete, integer or binary, stochastic or fuzzy decision variables (van Laarhoven and Pedrycz, 1983). Nevertheless, few suitable methods were proposed to approach these situations, which turns the method selection problem less demanding than in the frequently encountered MADM and MODM problems.

3.3 MCDA methods: the AHP

One of the most prevalent and popular approaches for MCDA is AHP. This problem-solving framework was originally developed by the mathematician Thomas Saaty (Saaty, 1986, 1990), in the late 70's, and belongs to the family of normative methods of the American school of thought. Albeit the severe criticism and heated debate that AHP has been subjected to by MCDA academics, its widespread application reflects its generalized acceptance by both the academic and practitioners communities (Dodgson et al., 2000).

The basic idea behind AHP is to convert subjective assessments of relative importance into a set of overall scores and weights (Dodgson et al., 2000). The assessments are subjective once they reflect the perception of the DM, and the importance is relative because it is based on pairwise comparisons of criteria and, in some cases, of alternatives.

The first step of AHP is to decompose the decision problem into a hierarchy of sub-problems, by arranging the relevant factors of the problem into a hierarchic structure that descends from an overall goal to criteria, sub-criteria and alternatives, in successive levels. According to Saaty (1990), the higher levels of the AHP hierarchy should represent the elements with global character (e.g. the main objective of the decision problem), while the levels with greater depth should be devoted to the elements that have a more specific nature (e.g. multiple criteria and alternatives). Resorting to this type of hierarchies provides the DM with an overall view of the complex relationships inherent in the decision problem, fostering a better understanding of the problem itself.

The second step of the method comprises the elicitation of pairwise comparison judgments from the decision making body. Here, the DM is asked to assess the relative performance of criteria with respect to the overall goal, through pairwise comparisons (e.g. criterion A with criterion B; criterion A with criterion C). The same procedure can be employed to appraise the alternatives, according to the degree to which they satisfy each criterion. The output of this preference elicitation process is a set of verbal answers of the DM, which are subsequently codified into a nine-point intensity scale. This semantic scale was proposed by Saaty (1986) and assumes discrete values from 1 (equally preferable) to 9 (strongly preferable), where the values 2,4, 6 and 8 represent intermediate values of preference.

One of the distinguishing characteristics of AHP is related to the fact that it is grounded in pairwise comparisons, which are often regarded as straightforward, intuitive and convenient means to extract subjective information from DM concerning their implicit preferences. However, pairwise comparison strategies rely on the assumption that the DM is consistent in his/her judgments, which is not always guaranteed in practice. To measure the degree to which the DM was consistent in his/her responses, a consistency index is computed for a given matrix. If its value is higher than a specific value (> 0.1) (Saaty, 1986, 1990) the matrix entries need to be amended since there were inconsistencies in the DM judgments.

The questions asked to the DM in the previous step of the AHP process aim at achieving two goals: derive and estimate the priorities, or weights, of criteria and establish the relative performance scores for alternatives in each criterion.

After the determination of the pairwise comparisons among criteria, AHP converts the corresponding DM evaluations into a vector of priorities, by finding the first eigenvector of the criteria matrix. This vector has information about the relative priority of each criterion with respect to the goal.

The following step of AHP, which involves the relative importance of criteria, can be performed using two approaches: one supported on the relative measurement of alternatives and another based on absolute measurements of these alternatives (Saaty, 1990). The former conducts separate pairwise comparisons for the set of alternatives in each criterion (and sub-criterion, if applicable), in order to elicit their performance scores. In the latter approach, the alternatives are simply rated in each criterion, by identifying the grade that best describes it (Saaty, 1990). Afterwards, a weighting and summing step yields the final results of AHP, which are the orderings of the alternatives based on a global indicator of priority. The largest value of this global score will correspond to the most preferred alternative.

Although this approach was initially developed for single decision making, it has already been adapted to group decision making (Saaty, 1989). In the GDM scenario, the aggregation of the individual priorities is usually performed by computing the weighted geometric mean of the normalized values of each DM involved in the process.

The main reasons behind the wide applicability of AHP are: its simplicity, since it does not involve cumbersome Mathematics; the relative ease with which it handles multiple criteria; its great flexibility, being able to effectively deal with both qualitative and quantitative data; and the ease of understanding (Ho et al., 2009; Kahraman et al., 2003). Besides, the consistency verification operation of AHP can act as a feedback mechanism for the DM to review and revise their judgments, thus preventing inconsistencies (Ho et al., 2009). However, despite these advantages, the drawbacks of AHP instigated a controversial debate among MCDA academics that raises doubts about the underlying theoretical foundations of the method. The major concerns are closely related to the rank reversal problem and the potential inconsistency of the nine-point scale proposed by Saaty (1986). The rank reversal occurs whenever the addition of one of the alternatives from the initial set modifies the final relative ordering of the alternatives (Goodwin and Wright, 2004). This situation may lead to different solutions, even if the relative judgments remain unchanged. Regarding the nine-point scale, it was identified a lack of theoretical foundation between the points used in the scale and the corresponding verbal description (Goodwin and Wright, 2004). The effect of the order of the elicitation process can also be understood as a problem because, since criteria priorities are elicited before the performance scores of alternatives, the DM is induced to make statements about the relative importance of items without knowing, in fact, what is being compared (Dodgson et al., 2000). According to Dyer (1990), one of the main flaws of AHP is the ambiguity of the elicitation questions, since they require that the DM explicitly, or implicitly, determines a reference point in the ratio scale. Seydel (2006) also mentions that the large number of comparisons required by AHP, especially when dealing with large number of criteria and/or alternatives, can turn the pairwise comparisons into a cumbersome and time-consuming task.

These lead us to use another method so that a more confident evaluation and analysis can be provided to the DM.

3.4 MCDA methods: MMASSI

The success of the theoretical developments that have been made on MCDA approaches relies heavily on the development of decision support systems that enable the DM to take advantage of the capabilities provided by the MCDA approaches proposed in the literature (Zopounidis and Doumpos, 2002). As said before, in here we perform a comparison of the results yielded by the well-known AHP method and the ones provided by the MCDA method proposed by Pereira and Fontes (2012), which will be thereafter referred to as MMASSI. This way, we're able to increase the level of confidence on the yielded results, by removing some of the constraints associated to the use of a single method. The underpinnings of MMASSI rely on existing normative methods, which were developed along the lines of the American school of thought. This methodology was originally devised to aid the decision support process involving a group of decision makers. However, to fit the scope of our research, we will adapt it to a single-decision maker (or a consensual group of them). MMASSI distinguishes from previously proposed MCDA methodologies in the sense that 1) it provides the DM with a pre-defined set of criteria that tries to generally cover all the relevant criteria in the field of application 2) it does not explicitly requires the presence of a facilitator, or analyst, to guide the DM throughout the decision process, since it is implemented in an user-friendly and self-explanatory software 3) it uses a continuous scale with two reference levels and thus no normalization of the valuations is required. The idea behind MMASSI is to enhance and hasten the decision process by providing an easy understanding of the method by forcing the user to perform a set of mandatory predetermined steps, which fosters the trust of DM in the process and promotes the widespread application of MCDA in organizational contexts.

MMASSI methodology encompasses a set of sequential steps that guide the DM through the several stages of a multi-criteria decision process. MMASSI begins by presenting the DM with a pre-defined set of criteria, along with their descriptions and suggestions on how to measure them. These criteria are chosen based on the *a priori* study of the decision context and subsequent identification of the features that are consensually considered relevant within its scope. This provisional family of criteria works as a starting point to guide the DM through the criteria selection. Nevertheless, it is the DM who defines and assesses the suggested criteria according to the following range of properties: completeness, redundancy, mutual independence and operationality (Seydel, 2006). In order to generate the final set of criteria, the DM can refine the starting set by removing, or modifying, or adding new criteria. After validating the criteria set, a set of alternatives is provided by the DM, or the analyst if one is involved, to the MMASSI system. The following stage comprises the employment of a weighting elicitation technique, namely the swing-weight procedure proposed by Winterfeldt and Edwards (1986), that sets up the relative criteria weights according to the preferences manifested by the DM. A fixed continuous scale with seven semantic levels with two references is presented to the DM so as to set up the ground values based on which he/she assesses each considered alternative against each selected criterion. The construction of this scale was based on earlier work by Bana e Costa and Vansnick (1999). The considered levels are the following: Much Worse, Worse, Slightly Worse, Neutral, Slightly Better, Better and Much Better. This stage implies a mandatory *a priori* definition of two reference scale levels, namely, the "Neutral" (or indifference level) and the "Better" levels, which are to be used to assess each alternative in each criterion. This interval scale is fully defined by the DM, taking into account the business and organizational context of the analysis, and it should mirror his/her preferences. Having defined the criteria, the possible courses of action and a continuous semantic scale, in the next phase the DM appraises each alternative by allotting a semantic level to each criterion.

The chosen level should reflect the subjective preferences and individual judgments of the DM in terms of the extent to which a given alternative achieves the objectives. The last step of MMASSI involves the computation of an overall score for each alternative, according to an additive aggregation model, and the subsequent ranking of the alternatives. Similarly to AHP method, the alternative ranked first is associated to the largest overall score and corresponds to the most preferred alternative. MMASSI also offers the possibility of performing a sensitivity analysis to assess the robustness of the preference ranking to changes in the criteria scores and/or the assigned weights. A sensitivity analysis measures the impact of small perturbations in the variables of the problem (e.g. criteria scores and criteria weights) in terms of alternatives, by means of the comparison of the modified ranking with the original one. The closer the rankings, the more robust the method is. These steps are important to increase the DM's confidence in the outcome of the multi-criteria decision analysis.

4 Case Study: Evaluation of Vehicle Painting Plans

The automobile industry has been one of hardest hit by the global financial downturn, which reflected in a sharp fall on industry sales. Due to this reason, the automobile plant where we carried out our case study is producing below capacity. Under such adverse circumstances, the management of the plant felt the need to optimize its processes. Since the painting process is (a) one of the most complex activities in automobile manufacturing, (b) a bottleneck in this specific plant, and (c) responsible for the highest costs (e.g. the painting sector costs represent a fraction of, approximately, 70% of the total expenditures of the entire plant), the management plant considered this sector to be the most critical to conduct a MCDA.

The purpose of this case study is twofold. On the one hand we illustrate the potential of the application of MCDA for solving a complex decision making problem in the painting sector of an automobile plant. On the other hand, we analyze the possible vehicle painting plans in order to provide the DM with an evaluation of the aforementioned plans, as well as with the identification of the one that contributes the most to the painting process optimization.

In this section we describe the decision problem under consideration, explain how the case study was carried out and present the obtained results, by traversing each one of the stages identified in Section 2.

4.1 Problem description

The target of our case study is one of the plants of Toyota, located in Ovar, Portugal. This plant employs around 320 employees and its main function is to perform the welding, painting and final assembly of a specific automobile model. The vehicle parts are delivered to the plant in batches. Each batch includes the necessary parts to assemble five vehicles. After selecting the necessary parts for production, according to the production planning, these parts are forwarded to the welding sector. The welded bodywork of the vehicles is then directed to the painting sector. Since our work focuses exclusively in this sector, we will later describe the painting process in detail.

The operations manager of the plant and the painting sector team are interested in optimizing the painting process, which is a bottleneck of this plant. The only way to improve this process is by optimizing the vehicle *painting plans*. These painting plans are defined as a combination of a vehicle model, which can be *simple* or *mixed*, with the

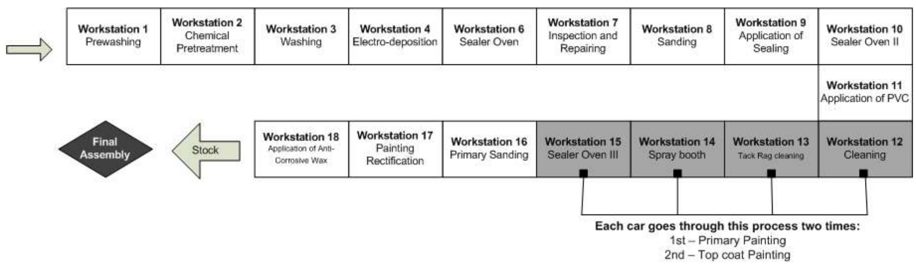

Figure 1: Illustration of the painting process.

number of distinct colors used to paint the vehicles, in a given day. Given this, the goal of this case study is to evaluate the vehicle painting plans, by sorting them in decreasing order of preference, as well as to identify the painting plan which contributes the most to the process optimization.

4.1.1 Description of the Painting Process

The painting sector comprises a production line which is made up of a series of work stations. Figure 1 shows the general flow of the painting process. When the vehicle bodywork (or cabins) enter the painting sector, they are first submitted to a prewash. The main process begins in the following station, where the surface of the cabins is prepared to the further application of coatings through a chemical pretreatment. Then, the vehicle parts are washed again and further submitted to the electro-deposition of an organic base coating. Afterwards, they are dried in a sealer oven and subjected to a manual inspection. If any defect is detected, it is repaired by manual sanding. The next stage consists in the application of sealing and PVC to prevent humidity penetration and corrosion. The sealing is dried in another sealer oven and then the cabins are cleaned. The cleaned vehicles are subsequently subjected to a primary painting, in a spray booth, and dried in a sealer oven. The goal of primary painting is to prepare the surface of cabins to the further application of a top coat. The operations performed at work stations 12, 13, 14 and 15 are repeated for the application of top coat. The process continues with the manual inspection of the physical aspect of the painted surface. In case defects are detected, they are repaired through manual sanding and rectification. The painting process ends with the application of anti-corrosive wax. The painted vehicles are then stocked in a temporary warehouse until forwarded to final assembly.

4.2 Data Gathering

The application of MCDA to this decision problem involved the operations manager of the plant and the painting sector team (henceforth decision maker, or simply DM). Albeit there are several people involved in the decision making process, they act as if they were a *single decision maker*, since the given answers represent the consensual views and preferences of both the manager and the painting sector team. A number of face-to-face meetings with the DM were convened, so as to understand the decision context and gather information regarding the decision problem, the possible alternatives and the relevant set of criteria. Each one of these meetings lasted approximately two hours.

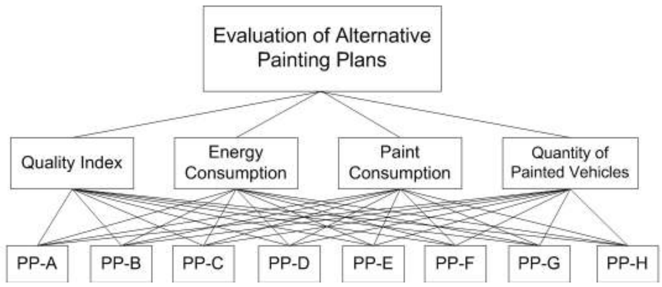

Figure 2: The decision hierarchy of the decision problem at hand. At the top level is the main goal of the decision making. The second level consists of the criteria that contributes to the overall goal. The third level is comprised of the alternatives that will be evaluated in terms of the criteria of the second level.

As previously mentioned, the goal of the DM is to optimize the painting sector of the plant through the optimization of the vehicle painting plans. The portfolio of alternatives was determined by identifying the most frequent painting plans based on daily historical data of the plant. The analyzed data referred to a time span of six months (June 2012 to December 2012). Using this procedure we identified eight alternatives, which will be referred to, in this paper, as PP-A (Painting Plan A), PP-B, PP-C, PP-D, PP-E, PP-F, PP-G and PP-H. These alternatives were validated by the DM and are described in Table 3.

The next step was the selection of the relevant set of criteria to be used to appraise each one the alternatives. Four quantitative criteria were considered after a brainstorming session with the DM, namely: the *quality index*, the *energy consumption*, the *paint consumption* and the *quantity of painted vehicles*. The *quality index* (QI) is given by the average number of defects per painted vehicle and, as the name implies, is a proxy for the quality of the performed painting. Defects can arise as a result of the manual painting process, which is performed by painters, or as a consequence of the ink quality. *Energy consumption* (EC) includes both the electricity and the gas consumption of the painting sector and is measured in kilowatts-hour (kWh). In turn, *paint consumption* (PC) reflects the direct cost of painting the vehicles (in terms of materials), being given by the average ink liters used to paint a given vehicle. The last criterion is the *quantity of painted vehicles* (QPV) per day. More detailed information regarding these criteria is given in the top part of Table 3.

Based on the gathered information, the decision problem is unbundled into its constituent parts using a AHP hierarchy tree structure comprised of three levels (overall goal, criteria and alternative painting plans), as depicted in Figure 2. This hierarchical tree has the advantage of providing an overall view of the complex relationships inherent in the decision problem, thus easing the understanding of the problem by the DM.

4.3 Elicitation of criteria weights

After structuring the decision problem at hand, the DM was asked to assess the relative importance of the identified criteria based on two different procedures: pairwise comparisons and swing-weight procedure of Winterfeldt and Edwards (1986). The former is used in the AHP method, whereas the latter is used in the MMASSI methodology.

These weights are (a) non-negative numbers, (b) independent of the measurement units

Table 1: AHP pairwise comparison matrix for criteria and the corresponding criteria weights.

	QI	EC	PC	QPV	**Criteria Weights**
Quality Index (QI)	1	3	7	9	0.606
Energy Consumption (EC)	1/3	1	2	7	0.23
Paint Consumption (PC)	1/7	1/2	1	5	0.126
Quantity of Painted Vehicles (QPV)	1/9	1/7	1/5	1	0.039

of the criteria, and are determined such that (c) higher weights reflect higher importance. The sum of the normalized weights equals 1, which implies that each criterion can be interpreted according to their proportional importance.

4.3.1 AHP

According to AHP, the assignment of weights to the chosen criteria is performed by asking the DM to form an individual pairwise comparison matrix using the nine-point intensity scale proposed by Saaty (1986). In this pairwise comparison matrix, the four criteria are compared against each other in terms of their relative importance, or contribution, to the main goal of the decision problem. Table 1 shows the pairwise comparison judgments provided by the DM, as well as the resulting criteria weights.

Based on the AHP results, the *quality index* was deemed the most important criterion ($w_{QI} = 60.6\%$) for the evaluation of the painting plans, followed by *energy consumption* ($w_{EC} = 23\%$) and *paint consumption* ($w_{PC} = 12.6\%$). The least important criterion is the *quantity of painted vehicles*, which was assigned a relative importance of merely 3.9%.

A pairwise comparison matrix is of acceptable consistency if the corresponding *Consistency Ratio* (CR) is $CR < 0.1$ (Saaty, 1986, 1990). Since we obtained $CR = 0.066 < 0.1$, the DM has been consistent in his judgments and, thus, the obtained criteria weights can be used in the decision making process.

4.3.2 MMASSI

Contrary to AHP, which relies on pairwise comparisons, the MMASSI method resorts to the swing-weight procedure to derive criteria weights. According to this procedure, the DM should first identify the most important criterion, which will be assigned a score of 100, and then successively allot scores (lower than 100) to the second, third and fourth most important criteria. The given scores should reflect the DM's order and magnitude of preference and are further normalized so as to obtain the criteria weights. Table 2 provides both the DM's scores and the resulting criteria weights.

The comparison of Table 2 with Table 1 shows a considerable similarity between the set of criteria weights obtained by AHP and the ones returned by MMASSI. This similarity indicates consistency in the DM's judgments. Once again, *quality index* is the criterion with the highest priority, with an influence of 58.8%, followed by the *energy consumption* ($w_{EC} = 23.5\%$), *paint consumption* ($w_{PC} = 11.8\%$) and *quantity of painted vehicles* ($w_{QPV} = 5.9\%$).

Table 2: Swing-weight scores, as given by the DM, and the corresponding normalized criteria weights obtained by MMASSI.

Criteria	**Swing**	**Weights**
Quality Index (QI)	100	0.588
Energy Consumption (EC)	40	0.235
Paint Consumption (PC)	20	0.118
Quantity of Painted Vehicles (QPV)	10	0.059
Total	170	1

Table 3: Performance Matrix. The best values observed for each criterion are underlined. The analysis of these values reveals that none of the alternatives achieves the best performance in all criteria, as expected.

Criteria	**QI**	**EC**	**PC**	**QPV**
Unit	# Defects	kWh	Ink liters	# Vehicles
Max/Min	Min	Min	Min	Max
Weights AHP	0.606	0.23	0.126	0.039
Weights MMASSI	0.588	0.235	0.118	0.059
PP-A (Simple + 1 Color)	3.45	87	2.02	15
PP-B (Simple + 2 Colors)	2.1	66	1.85	14
PP-C (Simple + 3 Colors)	<u>1.6</u>	60	1.59	<u>30</u>
PP-D (Simple + 4 Colors)	3.2	79	1.87	15
PP-E (Mixed + 1 Color)	2.1	81	<u>1.55</u>	11
PP-F (Mixed + 2 Colors)	3.0	73	1.58	21
PP-G (Mixed + 3 Colors)	2.8	72	1.64	16
PP-H (Mixed + 4 Colors)	2.5	<u>53</u>	1.56	15

4.4 Evaluation and Ranking of the Alternatives

In this stage, the alternative painting plans are appraised by the DM in terms of their contribution to the previously stated criteria. For obtaining this information, we have asked the DM to provide a numerical evaluation of the relative performance of each alternative painting plan for each considered criterion. These numerical evaluations are expressed using the scale adopted by each MCDA approach (e.g. AHP uses the nine-point intensity scale).

In order to assist the DM in this stage, we constructed a *performance matrix* by aggregating the daily data gathered by the painting sector, for a period of six months (June 2012 to December 2012). This matrix provides objective and quantitative information regarding the performance of each alternative on each relevant criterion, and served as a basis for the DM's evaluation.

After the completion of this stage, the alternatives' multi-criteria score (or *overall score*) is computed based on an aggregation procedure that takes into account, not only the alternatives' performance evaluation provided by the DM, but also the criteria weights. The final ranking is generated by sorting the alternatives in decreasing order of these overall scores.

Table 4: Mandatory reference scale levels of MMASSI, as defined by the DM, for each criterion.

Reference Scale Levels	Neutral	Better
Quality Index	1.8	1.6
Energy Consumption	27	21
Paint Consumption	1.79	1.66
Quantity of Painted Vehicles	12	21

Table 5: Final rankings yielded by AHP and MMASSI methods. The overall scores range from 0 to 100, with a higher score representing a higher level of preference.

AHP Ranking	AHP Overall Score	MMASSI Ranking	MMASSI Overall Score
PP-C	88.29	PP-C	64.64
PP-H	49.53	PP-E	51.05
PP-E	49.08	PP-B	33.69
PP-B	46.92	PP-H	28.09
PP-F	21.9	PP-G	22.95
PP-G	21.71	PP-F	21.72
PP-D	9.09	PP-D	12.96
PP-A	5.16	PP-A	8.72

4.4.1 AHP

After establishing a scale of priorities for the criteria, through paired comparisons, the DM is asked to appraise the different alternatives regarding each criterion. To perform this step, we adopt the *relative measurement of alternatives*, by conducting separate pairwise comparisons for the set of alternatives in each criterion. This elicitation process is based on a set of questions of the general form: "How much more does alternative 1 contributes to the achievement of criterion A than alternative 2?". The corresponding verbal answers of the DM are written down and subsequently codified into the nine-point scale of AHP. These relative performance scores constitute one of the inputs of a weighting and summing step that yields the final result of AHP.

4.4.2 MMASSI

Regarding MMASSI, the DM was first asked to set, for each criterion, the mandatory reference levels (*neutral* and *better* levels) of MMASSI fixed scale (cf. Section 3.4). These levels are expressed in the original units of measurement of criteria. The reflection instigated by the need to define these levels prompted the DM to review and adjust the painting sector goals for each criterion. The established levels are shown in Table 4. Taking into account these two reference levels, the DM appraises the set of alternatives, on each criterion, by assigning one of the following semantic levels to each alternative: Much Worse, Worse, Slightly Worse, Neutral, Slightly Better, Better and Much Better.

In this MCDA stage, the major differences between AHP and MMASSI are the following:

1. In contrast with AHP, MMASSI does not rely on pairwise comparisons, since each alternative is only assessed in terms of its contribution to each criterion;

2. Instead of using the potentially inconsistent nine-point semantic scale of AHP, MMASSI relies on a fixed interval scale that is fully defined by the DM.

4.4.3 Comparison of Results

After performing these evaluations, the alternatives have been ranked based on a global indicator of preference. From the analysis of Table 5, we deduce that the most preferred alternative is PP-C, since it is associated with the largest overall score of both AHP (leftmost columns) and MMASSI methods (rightmost columns). This alternative ranks first in both MMASSI and AHP final rankings. Based on these results, the panting plan with highest relative merit is the one involving the painting of simple vehicles with three different colors. From the business viewpoint, this result means that PP-C is the painting plan which contributes the most to the painting process optimization.

We resort to Kendall's tau rank correlation coefficient (Kendall, 1938), denoted as τ ($-1 \leq \tau \leq 1$), to perform a quantitative comparison of the similarity of the rankings returned by the two methods. Kendall's tau ($\tau = 0.79$) indicated the existence of a significant rank correlation between the AHP and MMASSI final rankings. This result means that, for this specific case study, both methods yield quite similar results.

4.5 Sensitivity Analysis

Since some steps of the MCDA process can be permeated by subjectivity and uncertainty, we considered relevant to validate our results by studying the impact of modifying the initially specified criteria weights on the MCDA rankings. For this purpose, we conducted a sensitivity analysis to determine how the final ranking of alternatives changes under different criteria weighting schemes. The results for both AHP and MMASSI have shown that small changes in the relative criteria weights did not make any impact on both the top (ie first and second positions) and the bottom (ie seventh and eighth positions) of the ranking, although some position shifts were observed in the intermediate ranking levels (namely, in the 3th and 6th positions). These conclusions also hold when introducing considerable changes on the criteria weights, and also for the case in which criteria have equal priorities.

5 Conclusions

In this paper, we present a case study on the application of MCDA to a complex decision problem arising in the painting sector of an automobile plant. The goal was to assist the management in the process of evaluating the relative merits of alternative painting plans, so as to optimize the painting sector of the plant. This problem is of great relevance for the company, since the painting sector is a bottleneck of the manufacturing process of the plant. Being aware that MCDA methods are prone to subjectivity and uncertainty, we resorted to two MCDA methods, namely the well-known AHP and the MCDA method proposed by Pereira and Fontes (2012) (MMASSI), in order to increase the confidence, reliability and robustness of the obtained MCDA results.

According to the point of view of the decision maker (DM), the MMASSI method proved to be more swift and easier to understand during the preference elicitation stage. This is partly explained by the use of a continuous, rather than semantic, scale. On the other hand, there is a sharp contrast between the number of judgments required by MMASSI in appraising the alternatives and the number of comparisons required by AHP, which is much lower using MMASSI. This characteristic of MMASSI turned the preference elicitation process less cumbersome for the decision maker when applying this method. Nevertheless, AHP proved to be more advantageous than MMASSI for structuring the decision problem and for stimulating the DM's reflection on the problem details.

The application of the MCDA methodology encouraged fruitful discussions and a deeper analysis of the problem peculiarities among the team. This reflection, along with the process of gathering and summarizing the historical data of the plant, helped the team determine the right key performance indicators and the corresponding target values for the painting sector. Other goals were also achieved, namely, by providing the team with a framework to address and solve complex problems in a more structured and scientific way.

Regarding the MCDA results on the evaluation of the alternative painting plans, the management found the results satisfactory and intends to use the final rankings to enhance the weekly planning of the painting sector.

We acknowledge that this study is limited in ways that suggest opportunities for future research. A possible direction would be to solve this decision problem using integrated approaches that combine the strengths of different MCDA methods. We also intend to explore more formally the distinguishing properties of MMASSI in relation with AHP.

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