Annals of Management Science
Vol. 3, No. 1, May 2014, 109-128

Multicriteria Decision Making: A Case Study in the Automobile Industry

Márcia Oliveira[*a], Dalila B. M. M. Fontes[a] and Teresa Pereira[b]

[a] *FEP, Faculdade de Economia da Universidade do Porto, and LIAAD/INESC TEC, Rua Dr. Roberto Frias, 4200-464 Porto, Portugal*

[b] *IPP/ESEIG, Escola Superior de Estudos Industriais e de Gestão, Instituto Politécnico do Porto, CIEFGEI, Rua D. Sancho I, 981, 4480-876, Vila do Conde, Portugal and Algoritmi Center, Universidade do Minho, 4800-058 Guimarães, Portugal*

Abstract

Multicriteria decision analysis (MCDA) has been one of the fastest-growing areas of operations research during the last decade. The research attention devoted to MCDA motivated the development of a great variety of approaches and methods within the field. These methods differentiate themselves in terms of procedures, theoretical assumptions and type of decision addressed. This diverseness of these methods poses a great challenge to the process of selecting the most suitable method for a specific real-world decision problem. In this paper, we present a case study for a real-world decision problem in the painting department of an automobile assembly plant. We solved the problem by applying the well-known AHP method and the MCDA method proposed by Pereira and Sameiro de Carvalho (2005) (MMASSI). By applying two MCDA methods rather than one, we expect to improve the robustness of the results obtained. The contributions of this paper are twofold: first, we intend to compare the results obtained with the two MCDA methods (i.e. AHP and MMASSI). Secondly, we intend to enrich the literature in the field with a real-world MCDA case study on a complex decision making problem, since there is a paucity of research work addressing real-world decision problems faced by organizations.

Keywords: *AHP, decision making, multicriteria decision analysis, multicriteria methodology, automobile industry.*

1. Introduction

In recent years, increasing competition in the global market as well as the burst of the so-called *Global Financial Crisis* have forced companies to re-engineer their processes in order to raise the levels of efficiency, responsiveness and flexibility. Against this background, applying the MCDA for solving strategic decision problems can turn out to be a very effective way of achieving an organization's performance goals.

[*] Corresponding author. E-mail: mdbo@inescporto.pt

MCDA is a formal quantitative approach to aid the decision making process by fostering in decision makers (DM) the development of a structured thinking of the decision problem at hand. The main motivation behind the development of this research field relates 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). Being aware of such hindrances, as early as 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 sought to make the decision making process more structured, transparent and efficient. Besides this, the application of MCDA in real-world problems helps increase the confidence of the decision makers in their decisions by helping them to reach a solution that complies with their preferences and system of values. Due to the interactive and iterative nature of MCDA process, its application to real-world scenarios may prove to be a daunting and time consuming task, which requires significant efforts 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 & Stewart (2002). These define 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 evaluating criteria. The alternative actions distinguish themselves by the extent to which they achieve the objectives, since, usually, none of the alternatives has the best performance for all objectives (Dodgson et al., 2000). Depending on the typology of the MCDA problem at hand, the best alternatives can be implicitly determined 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, the chosen alternative corresponds to the best compromise solution rather than to an optimal solution.

The views of academics, such as Belton & Stewart (2002), Seydel (2006) and Dooley et al. (2009), agree that MCDA prompts learning and 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 increased 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 application of its methods in real-world decision problems, are a reflection of the advantages of MCDA approaches in aiding decision making. Bearing this in mind, in this work, we will present a case study on a real-world decision problem in the painting department of one of Toyota's plants, using the well-known AHP method (Saaty, 1990) and the MCDA method proposed by Pereira & Sameiro de Carvalho (2005).

The contributions of this paper will be twofold: first, we will compare the results obtained with the two MCDA methods (i.e. AHP and MMASSI). Secondly, we will enrich the literature in the field with a real-world MCDA case study on a complex decision making problem, since there is a paucity of research work addressing real-world decision problems faced by organizations (see Dooley et al. 2009). On a different level, we believe that our research will encourage the adoption of a more structured thinking in problem solving by the decision makers in the organization from where this case problem is obtained and solved and in other organizations. Prior to this study, this particular organization had been mostly making their decisions based on business experience. We would like to note here 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. By embedding the principles of the scientific method into the decision-making process, decision makers will 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.

The remainder of this paper is organized as follows. Section 2 describes the steps involved in the deployment process of MCDA. Section 3 describes the MCDA methods used in the paper, namely, AHP and MMASSI. In Section 4, we provide a detailed description of the application of these methods to a real-world decision-making problem in the painting department of one of Toyota’s assembly plants. Section 5 presents concluding remarks, plans, and directions for further study.

2. MCDA Process

The deployment of MCDA is a non-linear recursive process comprising 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. 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 next step of the process involves the summarization of the information comprised in the performance matrix into a set of multicriteria 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 for each alternative that allows 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.

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. Before presenting these methods, we first introduce the main schools of thought in the field.

3.1. 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 *Analytic 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" while methods from the American school build "partial value functions on the set of alternatives, as well as a global value function" (Lootsma, 1990, page 282). 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 should be borne 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 may yield different results.

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. More specifically, if the problem has a continuous set of alternatives, it can be framed as a *Multi-objective Decision Making* (MODM) problem, whilst if the decision space is discrete, the problem falls within the category of *Multi-attribute Decision Making* (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 the 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 and stochastic or fuzzy decision variables (van Laarhoven & Pedrycz, 1983).

3.2. Methods

3.2.1. AHP

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

The basic idea behind the AHP is to convert subjective assessments of relative importance into a set of overall scores and weights. The assessments are subjective because they reflect the perception of the DM and are based on pairwise comparisons of criteria/alternatives. The first step of the AHP is to decompose the decision problem into a hierarchy of subproblems 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 lower levels should be devoted to the elements that have a more specific nature (e.g. multiple criteria and alternatives). Using 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 importance of criteria with respect to the overall goal, through pairwise comparisons (e.g. criterion A with criterion B; criterion A with criterion C and so on). 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 the AHP is the fact that it is grounded in pairwise comparisons, which are often regarded as straightforward, intuitive and convenient means to extract subjective information from the DM. 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), then 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, the 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 global goal. The following step of the AHP, which involves the relative importance of criteria, can be performed using two approaches. One is based on the relative measurement of alternatives while the other is based on absolute measurements of these alternatives (Saaty, 1990). In the former approach, separate pairwise comparisons for the set of alternatives in each criterion (and sub-criterion, if applicable) are carried out 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 them (Saaty, 1990). Afterwards, a weighting and summing step yields the final results of the AHP, which are the orderings of the alternatives based on a global indicator of priority. The alternative with the largest value of this global score is the most preferred one.

The main reasons behind the wide applicability of the 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 (Kahraman et al., 2003). Besides, the consistency verification operation of the AHP can act as a feedback mechanism for the DM to review and revise the judgments, thus preventing inconsistencies (Ho et al., 2009). However, despite these advantages, the drawbacks of the 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 to the potential inconsistency of the nine-point scale proposed by Saaty (1986). Rank reversal occurs whenever the addition of one alternative to the initial set of alternatives modifies the final relative ordering of the alternatives (Goodwin & Wright, 2004). This situation may lead to different solutions, even if the relative judgments remain unchanged.

Regarding the nine-point scale, it was argued that there is a lack of theoretical foundation between the points used in the scale and the corresponding verbal description (Goodwin & 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 the 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 the AHP, especially when dealing with a large number of criteria and/or alternatives, can turn the pairwise comparisons into a cumbersome and time-consuming task.

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

3.2.2. MMASSI

Here we perform a comparison of the results yielded by the well-known AHP method and the ones provided by MMASSI. This way, we are able to increase the level of confidence on the yielded results, by removing some of the constraints associated with the use of a single method. MMASSI was first proposed by Pereira & Sameiro de Carvalho (2005) and further extended to group decision making by Pereira & Fontes (2012). The underpinnings of MMASSI rely on existing normative methods, which were developed along the lines of the American school of thought. MMASSI can be distinguished from previously proposed MCDA methodologies in the sense that (a) 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; (b) 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; and (c) it uses a continuous scale with two reference levels and thus no normalization of the valuations is required.

MMASSI methodology encompasses a set of sequential steps that guide the DM through the several stages of a multicriteria 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, modifying, or adding 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 process comprises the application of a weighting elicitation technique, namely; the swing-weight procedure proposed by Winterfeldt & Edwards (1986), which sets up the relative criteria weights according to the preferences expressed 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 & Vansnick (1999). The considered levels are: 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 evaluate each alternative on 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, the DM, in the next phase, 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. Similar to the AHP method, the alternative ranked first is associated with 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. 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 multicriteria decision analysis.

4. Case Study: Evaluation of Vehicle Painting Plans

The automobile industry has been one of the most affected by the global financial downturn which led to a sharp fall on industry sales. Due to this reason, the automobile assembly plant where we carried out our case study was 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 costs represent a fraction of, approximately, 70% of the total expenditures of the entire plant), the plant manager considered this department to be the most critical to conduct a MCDA.

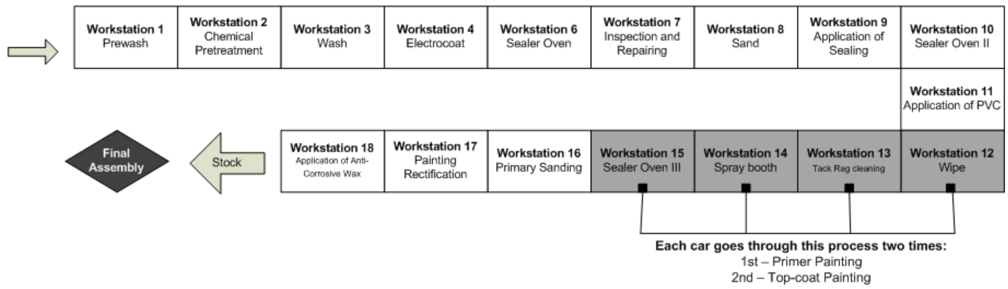

Figure 1. Illustration of the painting process

The purpose of this case study is twofold. First, to illustrate the potential ofthe application of MCDA for solving a complex decision making problem in the paint shop of an automobile assembly plant. Second, to analyze the different possible vehicle painting plans in order to provide the DM with the evaluations of these plans and to identify the plan that best optimizes the painting process.

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

4.1. Problem Description

The target of our case study is one of Toyota's assembly plants, located in Ovar, Portugal. The main purpose of this plant is to perform the welding, painting, and final assembly of a specific automotive model. The vehicle components are delivered to the plant in batches. Each batch includes the necessary components to assemble five vehicles. After selecting the necessary components for production, in accordance with the production planning, these components are forwarded to the body shop. The welded vehicle's body is then directed to the paint shop. Since our work focuses exclusively on this sector, we will later describe the painting process in detail.

The management is interested in optimizing the painting process, which is considered the bottleneck in the plant. The only way to improve this process is by optimizing the vehicle *painting plans*. These painting plans are defined as a combination of *vehicle cabin types*, which can be single or *mixed*, with different number of distinct colors used to paint the vehicles in a given day. Against this background, the purpose of this case study is to illustrate the potential of the application of MCDA for solving a complex decision making problem in the painting department of an automobile assembly plant and to provide the DM with an evaluation of the aforementioned painting plans as well as identifying the most preferred plan.

4.1.1. Description of the Painting Process

The painting department comprises a production line which is made up of a series of work stations. Figure 1 displays the general job flow of the painting process. When the vehicles bodies (or simply *cabins*, in this case) are transferred to the paint shop, they are first subjected to a prewash. The main process begins at the next station, where the surface of the cabins is cleaned and prepared for the subsequent application of organic coatings through a chemical pretreatment. The surfaces of the cabins are then washed again and further submitted to electro-coating. Afterwards, they are dried in an oven, with the purpose of baking the coat of paint and subjecting them to a manual inspection. If any defect is detected, it is repaired by manual sanding. This is followed by the application of sealing and PVC to prevent humidity penetration and protect from corrosion. The sealing is dried in another oven and then the cabins are wiped. The cabins are subsequently subjected to a primer painting, in a spray booth, and dried in an oven. The goal of the primer painting is to prepare the surface of the cabins to the top-coat application. The operations performed at work stations 12, 13, 14 and 15 are repeated when applying the top-coat.

The process continues with the manual inspection of the physical aspect of the painted surface. If defects are detected, they are corrected by manual sanding and rectification. The painting process ends with the application of anti-corrosive wax. The painted cabins are then stocked in a buffer stock until being forwarded to final assembly.

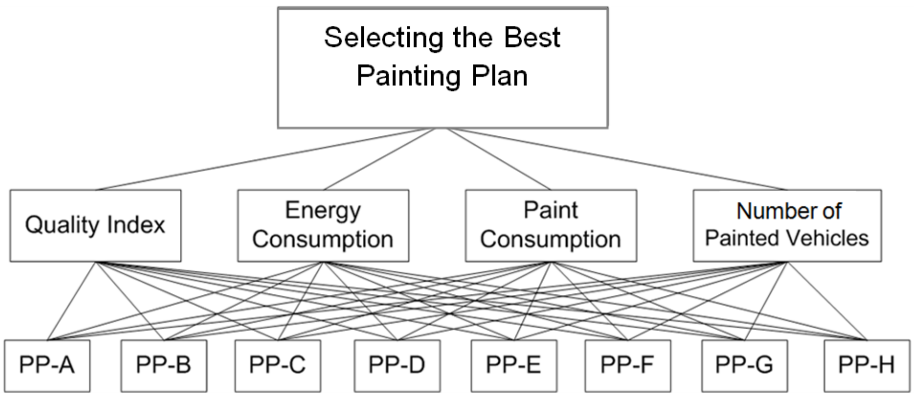

Figure 2. The decision hierarchy of the decision problem at hand.

4.2. Data Gathering

The application of the MCDA to this decision problem involved the operations manager of the plant and the paint shop management 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 paint shop 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 criteria.

As mentioned earlier, the goal of the DM is to optimize the global planning of the paint shop of the assembly 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 painting department.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, through to PP-H. These alternatives were validated by the DM and are described in Table 3.

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

	QI	**EC**	**PC**	**NPV**	**Criteria weights**
Quality Index (QI)	1	3	7	9	0.6055
Energy Consumption (EC)	1/3	1	2	7	0.2296
Paint Consumption (PC)	1/7	1/2	1	5	0.1255
Number of Painted Vehicles (NPV)	1/9	1/7	1/5	1	0.0394

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 number of painted vehicles. The quality index (QI) is given by the average number of defects per painted vehicle and, as the name implies, it 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). Note that, for the purpose of this research and for the sake of coherency, gas consumption was converted to 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 *number of painted vehicles* (NPV) per day. More information regarding these criteria is given in Table 3.

Based on the gathered information, the decision problem is unbundled into its constituent parts using the AHP hierarchy tree structure comprising three levels (overall goal, criteria, and alternative painting plans), as depicted in Figure 2. In this figure, we have the goal of solving the decision problem at the top or the first level of the hierarchy structure or tree. The second level consists of the criteria that contribute 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. The abbreviated alternatives are: painting plan A (PP-A), painting plan B (PP-B), and so on. 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 & Edwards (1986). The former is used in the AHP method while the latter is used in the MMASSI methodology.

These weights are non-negative numbers and independent of the measurement units of the criteria, and are determined such that higher values of the 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.

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
Number of Painted Vehicles (NPV)	10	0.059
Total	170	1

4.3.1. AHP

According to the 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 (1990). 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, quality index was deemed the most important criterion ($w_{QI} = 60.55\%$) for the evaluation of the painting plans, followed by energy consumption ($w_{EC} = 22.96\%$) and paint consumption ($w_{PC} = 12.55\%$). The least important criterion is the *number of painted vehicles*, which was assigned a relative importance of merely 3.94%.

A pairwise comparison matrix is of acceptable consistency if the corresponding Consistency Ratio (CR) is $CR < 0.1$ (Saaty, 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

In contrast to the AHP, which relies on pairwise comparisons, MMASSI uses the swing-weight procedure to derive criterion weights. According to this procedure, the DM should first identify the most important criterion, to which a score of 100 is assigned, and then successively allot relative 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 the AHP and the ones returned by MMASSI. This similarity indicates consistency in the DM's judgments. Once again, quality index is the criterion with highest priority, with an influence of 58.8%, followed by the energy consumption ($w_{EC} = 23.5\%$), paint consumption ($\mathrm{w_{PC}} = 11.8\%$), and finally number of painted vehicles ($\mathrm{w_{NPV}} = 5.9\%$).

Table 3. Performance Matrix. The best values observed for each criterion are underlined.

Criteria	**QI**	**EC**	**PC**	**NPV**
Unit	# Defects	kWh	Ink liters	# Vehicles
Max/Min	Min	Min	Min	Max
Weights AHP	0.6055	0.2296	0.1255	0.0394
Weights MMASSI	0.588	0.235	0.118	0.059
PP-A (Single + 1 Color)	3.45	87	2.02	15
PP-B (Single + 2 Colors)	2.1	66	1.85	14
PP-C (Single + 3 Colors)	<u>1.6</u>	60	1.59	<u>30</u>
PP-D (Single + 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. To obtain 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. the AHP uses the nine-point intensity scale).

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

Upon completion of this stage, the overall score of each alternative 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 the overall scores.

4.4.1. AHP

In this step, the DM is asked to appraise the alternatives by performing 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 intensity scale of the AHP. These relative performance scores constitute one of the inputs of a weighting and summing step that yields the final result of the AHP.

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
Number of Painted Vehicles	12	21

Table 5. Final rankings yielded by the 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

4.4.2. 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 (c.f. Section 3.2.2). 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 or Much Better.

In this MCDA step, the major differences between the AHP and MMASSI are the following: (a) in contrast with the AHP, MMASSI does not rely on pairwise comparisons, since each alternative is only assessed in terms of its contribution to each criterion; (b) instead of using the potentially inconsistent nine-point semantic scale of the 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 were 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 ranks first in both the AHP and MMASSI final rankings. Thus, the panting plan with highest relative merit is the one involving the painting of single cabins 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.

In order to compare the similarity of the rankings returned by the two methods, we compute Kendall's tau rank correlation coefficient (Kendall, 1938), denoted as τ $(-1 \leq \tau \leq 1)$. The obtained value, $\tau = 0.79$, indicates the existence of a significant rank correlation between the AHP and MMASSI final rankings, which means that 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 validated our results by performing a sensitivity analysis in order to determine how the final ranking of alternatives changes under different criteria weighting schemes. The results for both the AHP and MMASSI have shown that changes in the relative criteria weights did not make any impact on both the top (i.e. first and second positions) and the bottom (i.e. seventh and eight positions) of the ranking, although some position shifts were observed in the intermediate ranking levels (namely, in the third and sixth 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 and Plans and Directions for Further Research

5.1. Conclusions

In this paper, we report the application of MCDA to a case study on the automobile industry. The goal of this case study is to assist the management of the automobile assembly plant in the process of evaluating the relative merits of alternative painting plans, so as to optimize the painting process. This problem is of great relevance for the company, since the painting process is the bottleneck of the manufacturing process of the assembly plant. Being aware that MCDA methods are prone to subjectivity and uncertainty, we resorted to two MCDA methods, namely the well-known AHP and MMASSI, the MCDA method proposed by Pereira & Sameiro de Carvalho (2005), in order to increase the confidence, reliability, and robustness of the obtained results.

According to the DM's point of view, the MMASSI method proved to be swifter and easier to understand during the preference elicitation stage. This is partly explained by the use of a continuous scale, rather than semantic one, and by the requirement of a lower number of evaluations, when compared to AHP. Nevertheless, AHP proved to be more advantageous than MMASSI for structuring the decision problem. 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 to determine the right key performance indicators and the corresponding target values for the painting sector. Other goals were also achieved, namely: we were able to provide the team with a framework to address and solve complex problems in a more structured and scientific way. Regarding the MCDA results, the management found the results valuable and intends to use the final rankings to enhance the weekly planning of the paint shop.

5.2. Directions for Further Research

A possible direction for further research 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 to the AHP.

Acknowledgments

The funding by the ERDF (FEDER) through the COMPETE Programme and by FCT within the project PTDC/EGEGES/099741/2008 is acknowledged. First author was also funded by FCT, under the PhD grant SFRH/BD/81339/2011. The authors are also thankful to Toyota for providing the research scenario and the necessary conditions to carry out this case study.

References

Bana e Costa, A. C. & Vansnick, J.-C. (1999). The MacBeth approach: Basic idea, software and an application. In Meskens, N. and Roubens, M. (Eds.), *Advances in decision analysis* (pp. 131-157). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Belton, V. & Stewart, T. J. (2002*). Multiple criteria decision analysis: An integrated approach*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Brito, T. B., Silva, R. C. d. S., Botter, R. C., Pereira, N. N. & Medina, A. C. (2010). Discrete event simulation combined with multi-criteria decision analysis applied to steel plant logistics system planning. In *Winter Simulation Conference*, pages 2126–2137, Baltimore, MD, USA.

Dyer, J. S. (1990). Remarks on the analytic hierarchy process. *Management Science*, 36(3), 249-258.

Dodgson, J., Spackman, M., Pearman, A. & Phillips, L. (2000). Multi-criteria analysis: A manual. Technical report, Department of the Environment Transport and the Regions.

Dooley, A. E., Smeaton, D. C., Sheath, G. W. & Ledgard, S. F. (2009). Application of multiple criteria decision analysis in the New Zealand agricultural industry. *Journal of Multi-Criteria Decision Analysis*, 16(1-2), 39-53.

Goodwin, P. & Wright, G. (2004). *Decision analysis for management judgment*. (3rd ed.), Chichester, United Kingdom: John Wiley and Sons.

Hanne, T. (1999). Meta decision problems in multiple criteria decision making. In Gal, T., Stewart, T. J. & Hanne, T. (Eds.), *Multicriteria Decision Making: Advances in MCDM Models, Algorithms, Theory and Applications* (pp. 6.1-6.25). Boston, USA: Springer US.

Ho, W., Xu, X. & Dey, P. K. (2010). Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. *European Journal of Operational Research*, 202(1), 16-24.

Kahraman, C., Cebeci, U. & Ulukan, Z. (2003). Multi-criteria supplier selection using fuzzy AHP. *Logistics Information Management*, 16(6), 382-394.

Kendall, M. G. (1938). A new measure of rank correlation. *Biometrika*, 30(1/2), 81-93.

Lootsma, F. A. (1990). The French and the American school in multi-criteria decision analysis. *Recherche Opérationelle*, 24(3), 263-285.

Lu, J., Zhang, G., Ruan, D., & Wu, F. (2007). *Multi-objective group decision making: methods, Software and Applications with Fuzzy Set Techniques*. London, UK: Imperial College Press.

Pereira, T. & Sameiro de Carvalho, M. (2005). A decision support system for selection of Information Systems and Information Technologies in distribution companies. In Kulwant S. Pawar, Chandra S. Lalwani, José Crespo de Carvalho and Moreno Muffatto (Eds.), *Proceedings of the 10th International Symposium On Logistics: Innovations in Global Supply Chain Networks*. Lisbon, Portugal.

Pereira, T. & Fontes, D. B. M. M. (2012). Group decision making for selection of an information system in a business context. In *DA2PL'2012 Workshop: From Multiple Criteria Decision Aid to Preference Learning* (pp. 74-82). Mons, Belgium.

Roy, B. (1991). The outranking approach and the foundations of ELECTRE methods. *Theory and Decision*, 31(1), 49-73.

Hanne, T. (1999). Meta decision problems in multiple criteria decision making. In Gal, T., Stewart, T. J., & Hanne, T. (Eds.), *Multicriteria Decision Making: Advances in MCDM Models, Algorithms, Theory and Applications* (pp. 6.1-6.25). Boston, USA: Springer US.

Roy, B. (1999). Decision-aiding today: What should we expect? In Gal, T., Stewart, T. J. & Hanne, T. (Eds.), *Multicriteria Decision Making: Advances in MCDM Models, Algorithms, Theory and Applications* (pp. 1.1-1.35). Boston, USA: Springer US.

Saaty, T. L. (1986). Axiomatic foundation of the analytic hierarchy process. *Management Science*, 32(7), 841-855.

Saaty, T. L. (1989). Group decision making and the AHP. In Golden, B. L., Wasil, E. A., and Harker, P. T. (Eds.), *The Analytic Hierarchy Process: Applications and Studies* (pp. 59-67). New York, USA: Springer Berlin Heidelberg.

Saaty, T. L. (1990). How to make a decision: The analytic hierarchy process. *European Journal of Operational Research*, 48(1), 9-26.

Seydel, J. (2006). Data envelopment analysis for decision support. *Industrial Management and Data Systems*, 106(1), 81-95.

van Laarhoven, P. J. M. & Pedrycz, W. (1983). A fuzzy extension of Saaty's priority theory. *Fuzzy Sets and Systems*, 11(1-3), 199-227.

Winterfeldt, D. V. & Edwards, W. (1986). *Decision analysis and behavioral research*. Cambridge, New York, USA: Cambridge University Press.