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Comparison of Multi-Criteria Decision-Making Methods for Equipment Selection

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Abstract

Equipment selection is a complex task that requires the consideration of multiple criteria with different measurement units. A number of decision-making methods have been proposed for analysing equipment selection problems, each having their own distinctive advantages and limitations. Despite the number of decision-making techniques available, few comparative studies exist that evaluate two or more methods with a singular problem. This paper evaluates three multi-attribute decision-making methods for an equipment selection problem in the early stages of a chemical manufacturing process.

A software framework which incorporates Analytical Hierarchy Process (AHP), Multi-Attribute Range Evaluations (MARE) and ELimination Et Choix Traduisant la REalité trois (ELECTRE III) was developed and distributed to a technology manager at Fujifilm Imaging Colorants Ltd (FFIC). The manager, within a team of nine people examined the same decision problem using the three decision analysis methods. The results of the study are examined in respect to assessing each methods ability to provide accurate representations of the decision-makers' preferences and the ability to comprehend the uncertainty present. The decision-makers' identified MARE as their preferred method, AHP was found to be comparatively more time-consuming and showed the highest variation of results while ELECTRE III was unable to provide a conclusive best result.

Keywords: Multi-Criteria Decision-Making, Analytical Hierarchy Process (AHP), Multi-Attribute Range Evaluations (MARE), ELECTRE III, Equipment Selection.

1. Introduction

Equipment selection is an important activity for effecitve product and process development. Selecting the wrong equipment can be costly with respect to product quality, production time, production rate and over/under use of resources. Chakraborty and Banik (2006) stated that "selecting material handling equipment under constrained operating conditions is a complicated task, due to many feasible alternatives and conflicting objectives". They suggest that an "effective and efficient multi-criteria decision making tool" should be used to address equipment selection problems. However, despite the profiency of Multi-Criteria Decision-Making (MCDM), there is a paucity of literature demonstrating industrial applications by comparing different decision-making methods. The few comparitive studies of MCDM that exist are mostly related to healthcare and housing such as the comparison of Analytical Hierarchy Process (AHP) and Evidential Reasoning for selecting healthcare infrastructure locations (Dehe & Bamford, 2015), the comparison of ELECTRE IV and Genetic Algorithms for diagnosing Alzheimer's disease (Brasil Filho, et al., 2009) and the comparison of the weighted sum method, weighted product method, AHP, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Complex Proportional Assessment (COPRAS) for sustainable housing affordability assessment (Mulliner, et al., 2015). The majority of MCDM related literature on equipment selection focuses on assessing one particular decision-making method with a singular problem (Safari, et al., 2013; Yilmaz & Dagdeviren, 2011). This is an issue as different methods can yield different results when applied to an identical problem and thus it is important to examine the compatability of different methods with a particular type of decision problem (Malczewski & Rinner, 2015).

This paper compares a newly developed multi-attribute evaluation method, Multi-Attribute Range Evaluations (MARE), with the AHP and ELimination Et Choix Traduisant la REalité trois (ELECTRE III) by means of a case study conducted by Fujifilm Imaging Colorants Ltd (FFIC). The aim of the comparison is to evaluate the methods' ability in terms of providing meaningful results and in handling uncertainty for an industrial problem. The following section discusses the salient features of MCDM methods with respect to the challenges of equipment selection.

2. Method Selection

A number of different MCDM techniques have emerged to sort, rank or quantify alternatives based upon Pareto optimal selection. These methods can be separated into two distinct categories, Multi-Attribute (MA) methods and Outranking methods. MA methods aggregate a decision problem into a function which is maximised providing a numerical result for each alternative. Outranking methods determine pairwise outranking assessments of each pair of alternatives to sort or rank the alternatives. Both method types are used to evaluate problems where there are a finite number of decision alternatives (Malczewski, 1999).

Some of the most prominent MA methods are Analytic Hierarchy Process (AHP) (Saaty, 1980), Analytic Network Process (ANP) (Saaty, 1996), Weighted Sum (Zadeh, 1963) and Technique for Order Preference by Similarity to Ideal Situation (TOPSIS) (Hwang & Yoon, 1981). Within these methods, AHP has received the most academic interest (Huang, et al., 2011). Huang et al (2011) suggests "the wide use of AHP may be related to the availability of user-friendly and commercially supported software packages and enthusiastic and engaged user groups". The AHP method has been both disputed (Smith & Winterfeldt, 2004) and highly acclaimed (Gass, 2005; Oliveira, et al., 2014) by a number of academics. One of the primary reasons AHP is disputed is due to an inherent flaw termed rank reversals that occurs when an alternative is added or removed from a decision model after preferences have been provided. The outcome of which can adjust the results of the AHP analysis, sometimes reversing the order of preference. This flaw can be avoided by ensuring the decision problem is structured correctly prior to the decision analysis.

The two most prominent Outranking families are ELimination Et Choix Traduisant la REalité (ELECTRE) (Roy, 1968) and Preference Ranking Organisation METHod for Enrichment Evaluations (PROMETHEE) (Brans, 1982). Both families contain multiple methods which are generally considered to be from the French or European school of thought. Consequently, the literature regarding these methods is predominantly written in French. However, the majority of the key articles have been translated into English and have gathered support from a number of international research groups. Salminen et al. (1998) suggests that ELECTRE III is the most superior outranking methodology as it uses thresholds for modelling imprecise data.

Recently, a new MA method termed Multi-Attribute Range Evaluations (MARE) (Hodgett, 2013) was proposed for addressing decisions faced throughout chemical product and process development. The method “utilises a global sensitivity analysis to account for uncertian selections” (Hodgett, 2013) as Stewart (2005) proposed that a sensitivity analysis is a straightforward technique for addressing uncertainty. He stated that fuzzy based approches, which are increasingly being used with MCDM methods (Kahraman, et al., 2015; Farsi, et al., 2012; Khandekar & Chakraborty, 2015), overcomplicate the the already complicated decision-making process.

Although a case study utilising MARE was discussed by (Hodgett, et al., 2014) no comparison was made against other prominent MCDM methods. Therefore, AHP and ELECTRE III were chosen to benchmark the efficiency of each methods’ ability to provide meaningful results and in handling uncertainty. Recognising and understanding uncertainty is a major challenge in equipment selection, particularly at the beginning of product development as there will be an absence of data and knowledge regarding the product and process. The following section introduces the ChemDecide framework which was used to evaluate the three MCDM methods.

3. ChemDecide Framework

The ChemDecide framework consists of four software tools, one related to problem structuring and the other three are associated with the analysis (Figure 1). The problem structuring tool is termed Decision Setup while the analysis tools are known by their respective methodological names, AHP, MARE and ELECTRE III. The rationale for developing an independent problem structuring tool was a consequence of the following:

- Problem structuring is often overlooked in a decision-making process (Belton & Stewart, 2010) and by having a separate tool to guide the user through this phase forces them to consider their selections in a detailed yet structured manor.
- AHP suffers from rank reversals. Prohibiting the user from adding or removing alternatives and criteria from the decision model ensures rank reversals cannot occur.
- Separating the problem structuring phase from the decision-making procedure will ensure the decision problem remains consistent throughout all three analyses. Hence, comparative results will be attained from the industrial evaluations and the conclusions drawn.

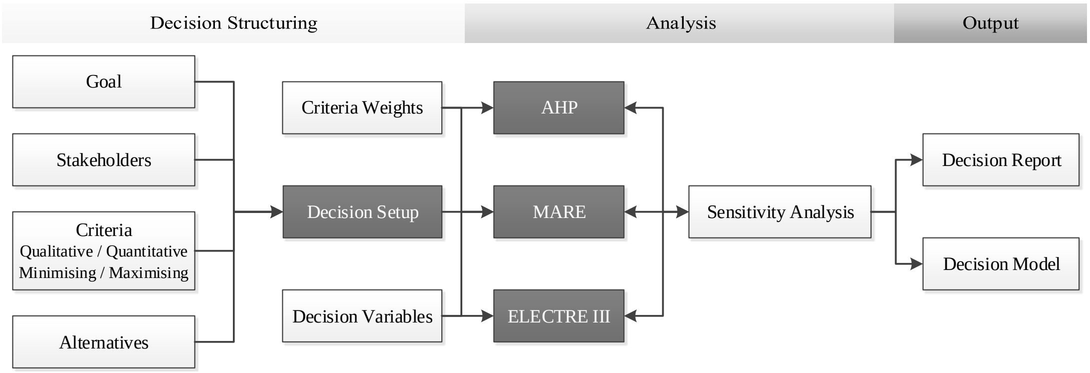

Figure 1 ChemDecide framework

As shown in Figure 1, the problem structuring tool requires the decision-maker(s) to define a goal, a set of alternatives and a defined set of criteria (including if each criterion is qualitative/quantitative and minimising/maximising). Decision Setup compiles this information into a single file which can be accessed by any of the three analysis tools. The analysis tools, which calculate a decision result, require the decision-maker(s) to input criteria weights and decision variables along with the rationale for each selection. These inputs can be altered to investigate the sensitivity of the results. Once a decision outcome is accepted, the analysis tools can compile all of the decision information into a single file or generate a report containing the results.

The goal of Decision Setup is to guide the user through the selection and verification of a feasible set of alternatives and criteria. The whole process should be sufficiently flexible to allow for changes as the decision-maker becomes more immersed in the problem. Figure 2 provides a flow diagram of the process utilised in Decision Setup and the iterative procedure that is built-in to ensure that the decision-maker identifies appropriate criteria and alternative sets.

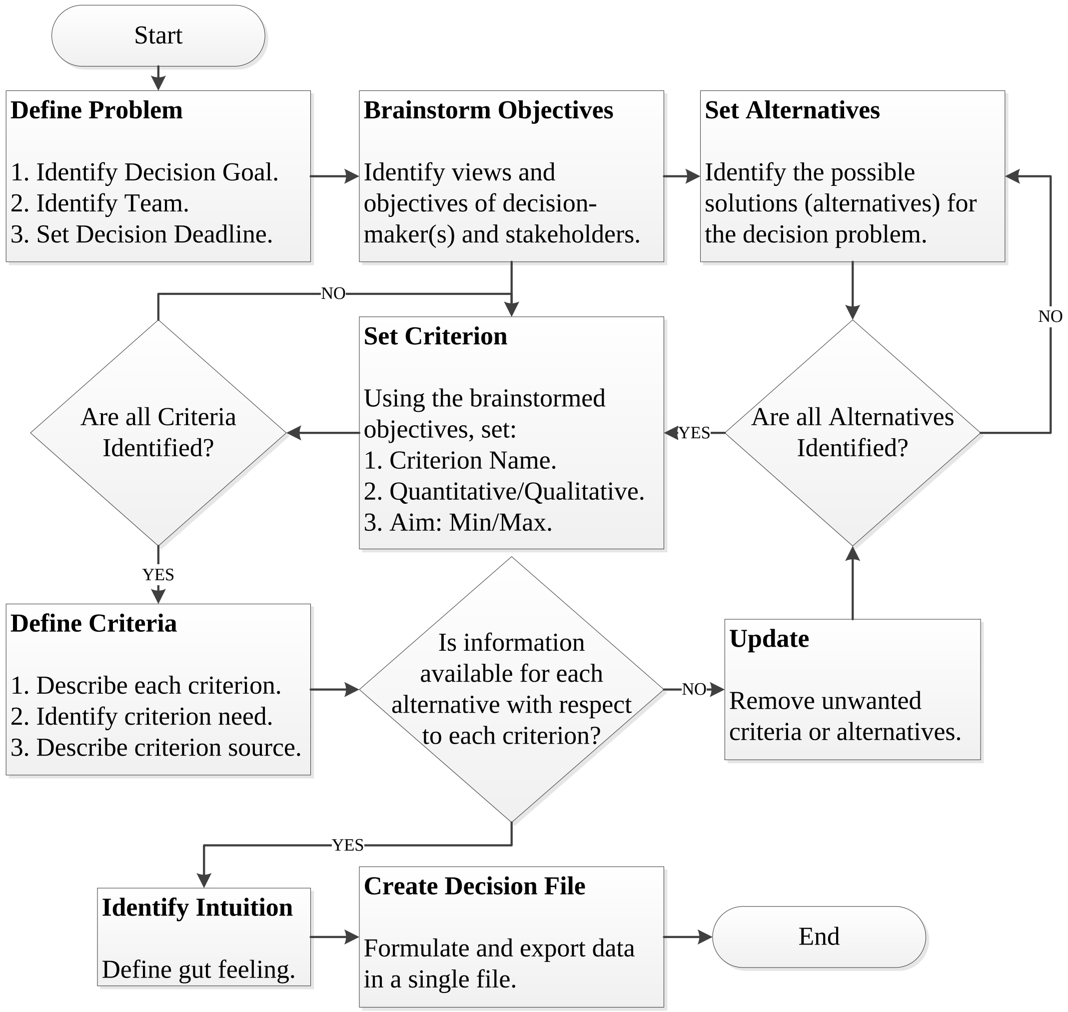

Figure 2 Decision Setup Logical Overview

Firstly, the decision-maker must identify the decision goal, record the team membership and schedule a deadline for the completion of the analysis. The decision-makers can then brainstorm whist considering external stakeholders to attain a perspective of the views and objectives of the decision problem. Although this information is not used directly in the analysis, the procedure focuses the users thought process on the problem and potentially associated issues. The next stage is to determine the decision alternatives followed by their related criteria. To aid in the selection of the criteria, the values and objectives discussed during the brainstorming section can be reviewed. Along with a criterion name, the decision-maker must identify if it is qualitative or quantitative (criteria source) and whether it is to be minimising or maximising (aim). The team can then define the criteria in more detail by recording a description of why each criterion is essential and provide a data source. This information is useful if the decision-maker wants to return to the decision analysis in the future or generate an analysis report. This feature of the framework adds value in terms of explicit reasoning, improved organisational learning and corporate memory for future use.

The final task of Decision Setup, which is critical to the analysis, requires the team to review the criteria and alternatives to ensure that it is possible to represent each decision variable by a numerical value or a subjective score. If the team cannot source representation, the decision-maker can return to a previous part of the procedure to update the criteria and alternative sets as shown in Figure 2. If the review is successful, the team can identify an alternative to represent their intuition (gut feeling) and complete the decision structuring process.

The AHP module guides the decision-maker through the Analytical Hierarchy Process (Saaty, 1972, 1980). The workflow for this process is given in Figure 3. The decision-maker uses a file created in Decision Setup which generates the interface for pairwise comparisons of the criterion. The user’s pairwise preferences are collected into a reciprocal matrix which is used to calculate the principle eigenvectors that represent the criteria weights. A consistency check is carried out to ensure the decision-maker has not violated transitivity. The method for calculating the principle eigenvectors and for checking transitivity was explained by Saaty (1980).

After the criteria weights are established, the decision-maker needs to pairwise compare each of the alternatives in respect to each of the criteria. Pairwise comparisons are collected for the qualitative criteria and numerical scores are provided for the quantitative criteria. The final scores are calculated and the results are shown along with an analysis chart that presents the decision variables on a spider diagram. The user can conduct a sensitivity analysis by

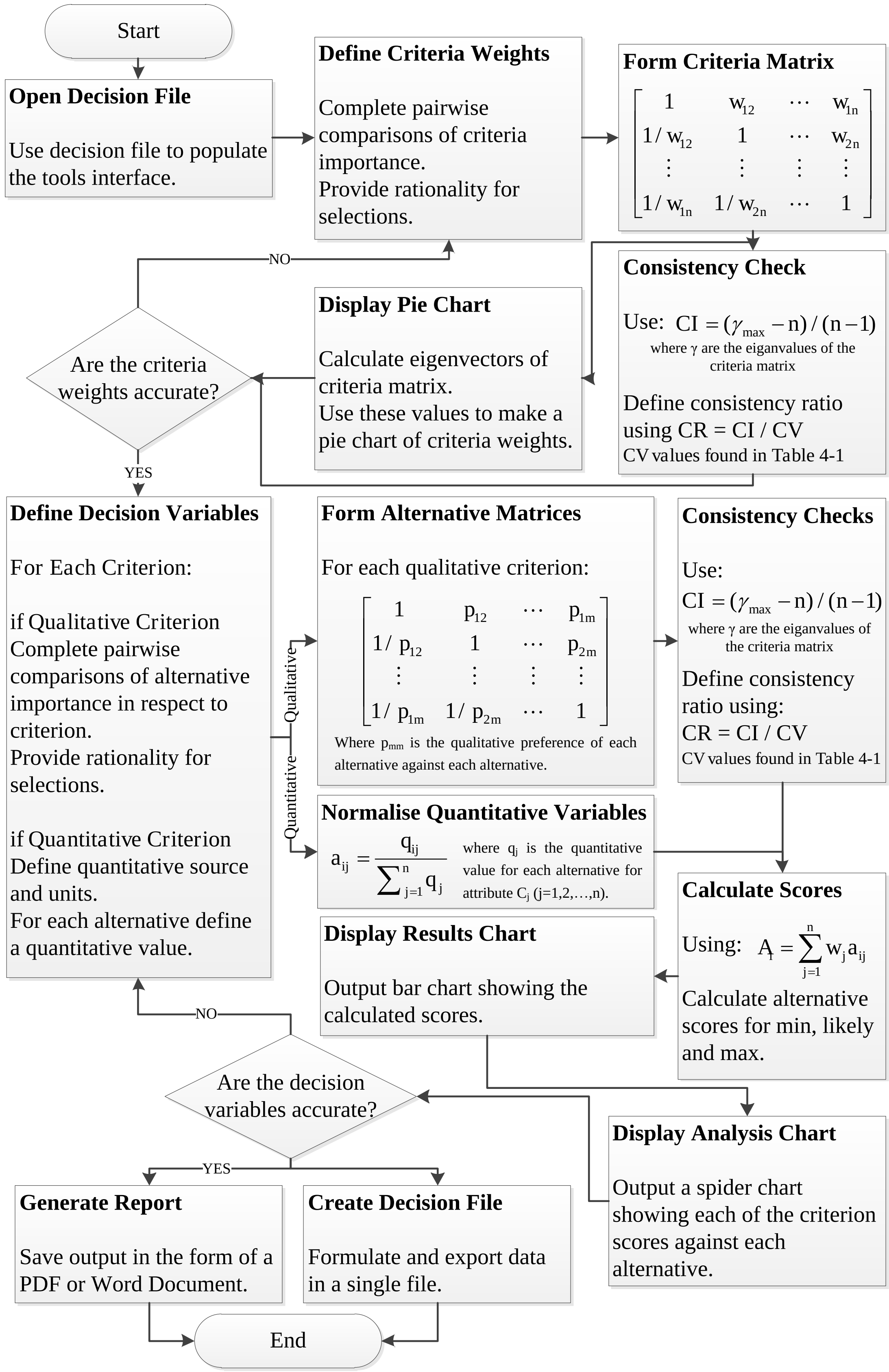

Figure 3 AHP Logical Overview

modifying the criteria weights and/or decision variables. On completion, a report can be generated or a decision file containing all the decision-makers' preferences can be exported.

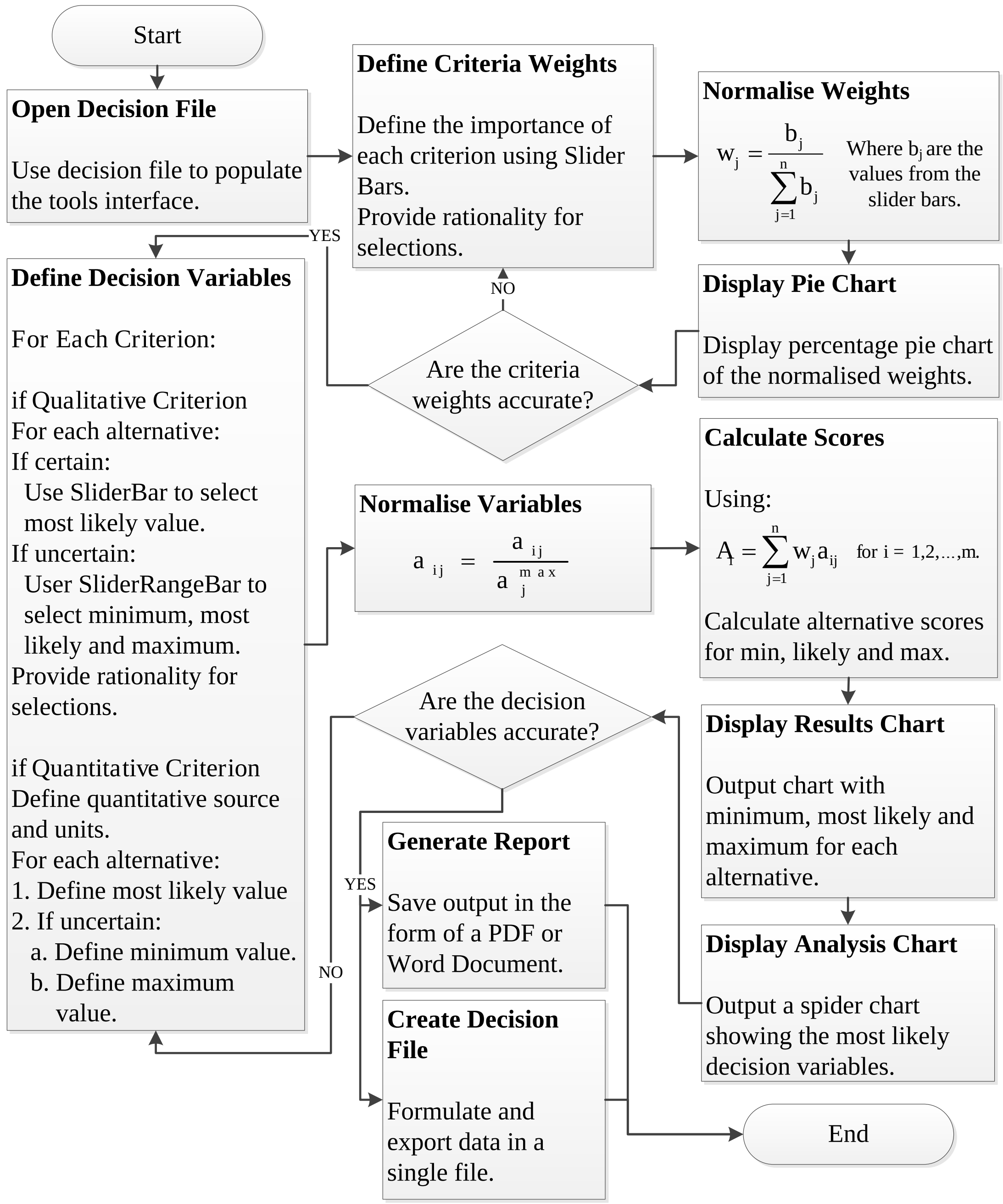

Figure 4 MARE Logical Overview

The MARE module guides the decision-maker through Multi-Attribute Range Evaluations (Hodgett, 2013) as shown in Figure 4. Initially, the decision-maker must define the criteria weights using a slider bar for each criterion. These weights are normalised and displayed on a pie chart. The decision-maker must then define the alternative scores in respect to each

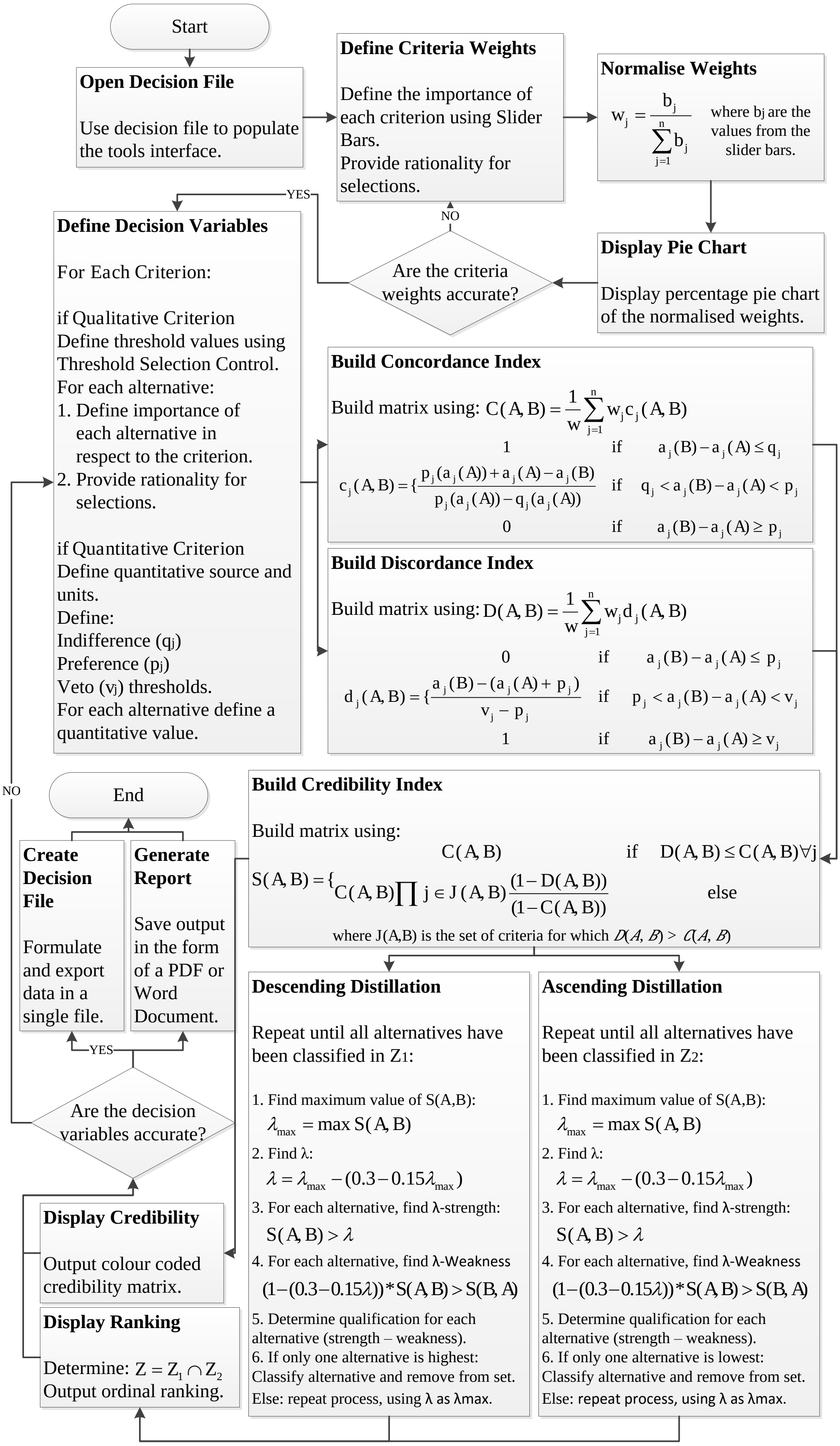

Figure 5 ELECTRE III Logical Overview

criterion. Slider bars with a single slider are used to input scores for certain selections and slider bars with three sliders are used to input scores for uncertain selections, as demonstrated by (Hodgett, et al., 2014). For decision variables with respect to quantitative criterion, numerical values are required, one if certain and three if uncertain (minimum, most likely and maximum). Final scores are calculated using the Weighted Sum Method (WSM) as shown in Figure 4 and displayed to the user. At this stage, a sensitivity study can be conducted, a report can be generated or a file containing the decision information can be saved.

The third analysis module guides the decision-maker through using ELECTRE III (Roy, 1978). The workflow for this is shown in Figure 5. Firstly, the decision-maker must define the criteria weights. This is accomplished in an identical way to the MARE module by using slider bars and a normalisation procedure. The decision-maker must then define decision variables and threshold values. Three threshold values are required for each criterion: indifference (q_j), preference (p_j) and veto (v_j). Decision variables with respect to qualitative criteria are input with slider bars and decision variables with respect to quantitative criteria are input as numerical values. Similarly, threshold values in respect to qualitative criteria are input with a slider bar with multiple sliders and threshold values in respect to quantitative criteria are input as numerical values. The procedure explained by Roy (1978) is used to calculate an ascending, a descending and final ranks. Similarly to AHP and MARE, the ELECTRE III module allows for a sensitivity study to be conducted and for file/report generation. A comparison of the three analysis tools is shown in Table 1.

The ChemDecide framework was developed using C# in Microsoft Visual Studio using .NET Framework. This approach was adopted for the following reasons:

- The ChemDecide framework can be installed and executed as a standalone software without the requirement for external software packages, thereby encouraging professionals from the chemical-using industries to evaluate the software.
- The .NET framework provides a range of libraries for input/output controls and data visualisation charts which could be incorporated into the ChemDecide graphical user interface.
- There are external libraries available on-line that have free licences for mathematical and algorithmic support.

Table 1 Comparison of the three analysis tools

	AHP	MARE	ELECTRE III
Method Summary	1. Decision problem modelled in a hierarchy. 2. Pairwise comparisons are used for qualitative measurement. 3. Scores are provided by eigenvector calculations.	1. Minimum, most likely and maximum scores can be used for measurement. 2. Scores aggregated using weighted sum method. 3. Uncertainty can be visualised.	1. Thresholds used to calculate pairwise comparisons of alternatives. 2. Positive and negative aspects of each alternative creates credibility index. 3. Ranking calculated.
Input	Quantitative scores, pairwise comparisons.	Qualitative and Quantitative scores, weights.	Qualitative and Quantitative scores, thresholds, weights.
Output	Cardinal scores	Cardinal scores	Ordinal rank
DM Interaction[a]	High	Moderate	Moderate
Uncertainty	Not considered directly[b]	Visualised in output	Fuzzy (pseudo-criteria)
Strengths	1. Pairwise comparisons provide an uncomplicated way to enter qualitative preferences.	1. Algorithm is relatively straightforward to use. 2. Output provides much information.	1. Very poor performance on a single criterion may eliminate an alternative from consideration[c].
Limitations	1. Possibility for intransitive preferences. 2. High number of pairwise comparisons required for large scale problems.	1. Further decisions may have to be considered upon reviewing the output.	1. Algorithm used is relatively complex and may not be understood by the DM. 2. A complete ranking of the alternatives may not be achieved.

[a] from Malczewski (1999). [b] from Millet & Wedley (2003) . [c] from Linkov et al. (2006).

The only limitation of C# and .NET is that the ChemDecide framework can only be compiled for use on a Windows based operating system. The following section discusses a case study utilising the ChemDecide framework that was conducted by Fujifilm Imaging Colorants Ltd (FFIC).

4. Case Study

The case study was provided by a technology manager at Fujifilm Imaging Colorants Ltd (FFIC) who had over 15 years' experience in industrial process engineering and a postgraduate degree in chemical engineering. Along with the technology manager, eight other people were present during the decision structuring and analysis, all of which had different job roles, levels of education and experience. The decision was to select the optimum equipment to mix a substance in the early stages of process development (a process which the decision-maker refers to as premixing). The product and different equipment options were not disclosed for confidentiality reasons hence the four alternatives are referred to as method 1, 2, 3 and 4. The decision-maker and team used Decision Setup to identify ten criteria on which to base their decision (Table 2).

Table 2 Criteria for case study

		Source	Aim	Rationalisation
c1	Capital cost at 50	Quantitative	Minimise	Capital expenditure is limited.
c2	Capital cost at 100	Quantitative	Minimise	
c3	Ease of clean down	Qualitative	Maximise	Multi-product plant.
c4	Complexity of solids feeding required	Qualitative	Minimise	Different options may place different demands on solids feeding equipment.
c5	Ease of operation	Qualitative	Maximise	Multiple concurrent operations on plant.
c6	Mechanical reliability	Qualitative	Maximise	Impact of outage significant.
c7	Material losses	Qualitative	Minimise	Material is of high value.
c8	Ease of modelling at lab scale	Qualitative	Maximise	Lab tests may be required.
c9	Quality of vendor support	Qualitative	Maximise	Rapid support is necessary.
c10	Power requirements	Qualitative	Minimise	Power needs kept to a minimum.

The overarching aim for FFIC was to select an equipment option which is inexpensive, straightforward and reliable to operate. Of the ten criteria chosen to model the decision, two were quantitative and represented by estimated values of capital expenditure for producing different capacities of product. Criterion c1 ('capital cost at 50') referred to the initial design capacity and c2 ('capital cost at 100') is the capacity if future expansion is required. The eight qualitative criteria were related to the ease and reliability of production and thus, as no quantitative data was available, they were represented by the decision-makers' subjective preferences.

Of the four equipment options, method 4 was the least expensive in terms of running costs. However, this equipment option was difficult to clean, had poor vendor support, would lose considerable amounts of valuable material during operation and was challenging to model at a laboratory scale. Methods 1 and 2 would have the lowest running costs at the current rate of production but would become more expensive if expansion was required. The running costs of implementing method 3 would remain constant if expansion was required but this method would lose the highest amount of valuable material, had the highest power consumption and would be difficult to clean.

4.1 Criteria Weights

Due to the large number of criteria in this analysis, the AHP module required 45 pairwise comparisons to calculate the criteria weights. Although this necessitated significant levels of input, the resulting pairwise comparisons were consistent. Both the MARE and ELECTRE III analyses required ten slider bar selections to determine the criteria weights. From studying the comparison of weights (Figure 6), it is apparent that AHP had placed greater emphasis on c5 (‘ease of operation’), c3 (‘ease of cleandown’), c4 (‘complexity of solids feeding required’), and c6 (‘mechanical reliability’) whilst placing less weight on the remaining criteria. The differences between the MARE and ELECTRE III criteria weights was less significant, with only c7 (‘material losses’), c6 (‘mechanical reliability’) and c10 (‘power requirements’) showing minor inconsistencies.

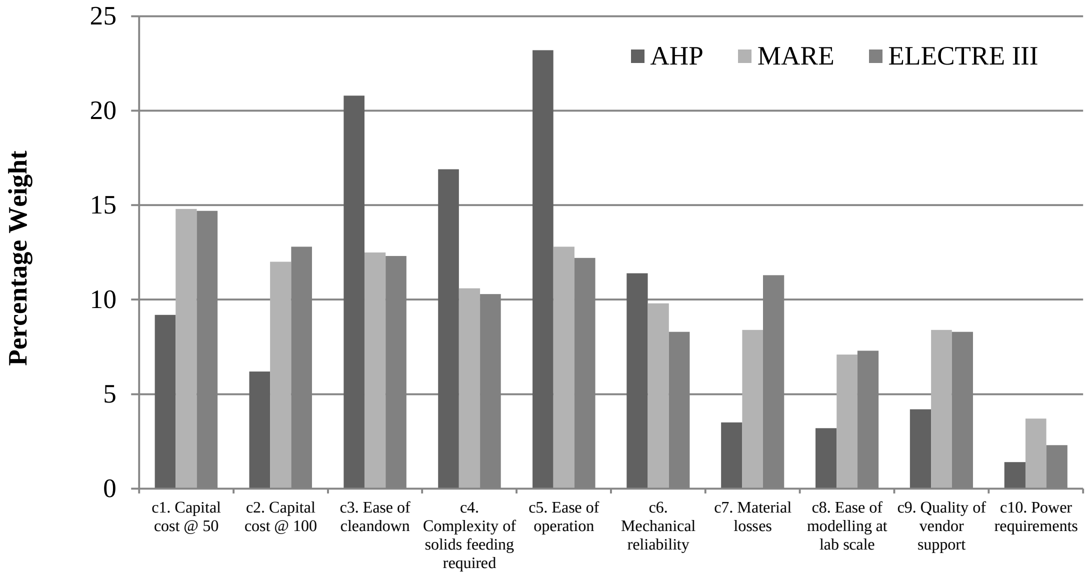

Figure 6 Comparison of the three analyses criteria weights

4.2 Alternative Scores

As there were four alternatives, the decision-maker was required to select six pairwise comparisons for each qualitative criterion and enter four numerical values for each quantitative criterion in the AHP analysis. The consistency checks determined that each pairwise comparison set provided by the decision-maker was transitive and consistent. In the MARE analysis, the decision-makers chose to apply minimum and maximum values to define the uncertainty for all of the alternative scores in respect to the quantitative criteria but chose only to apply one minimum and maximum selection to the alternative scores for the qualitative criteria. This one selection was for method 2 in terms of c5 (‘ease of operation’) and it is clear from Figure 7 that the most likely value of method 2 outperforms the other alternatives, however the minimum value selected is similar to the most likely values of the other alternatives, meaning in a worst case scenario, method 2 could perform similarly to methods 1, 3 and 4.

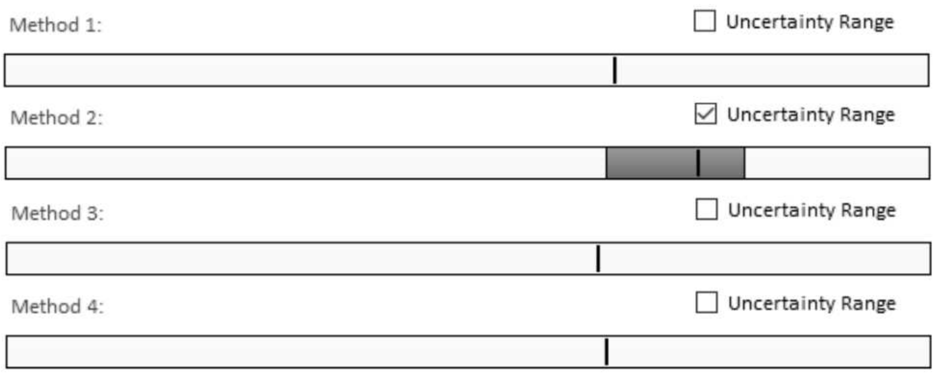

Figure 7 Minimum/Maximum selection for c5 (‘ease of operation’)

In the ELECTRE III analysis, the decision-makers used the same numerical values as used in the AHP and MARE analyses to determine the alternative scores for the two quantitative based criteria, c1 (‘capital cost at 50’) and c2 (‘capital cost at 100’). However, the alternative scores for the qualitative based criteria differed from the AHP and MARE analyses, as shown in Figure 8. These inconsistencies are examined in the discussion section.

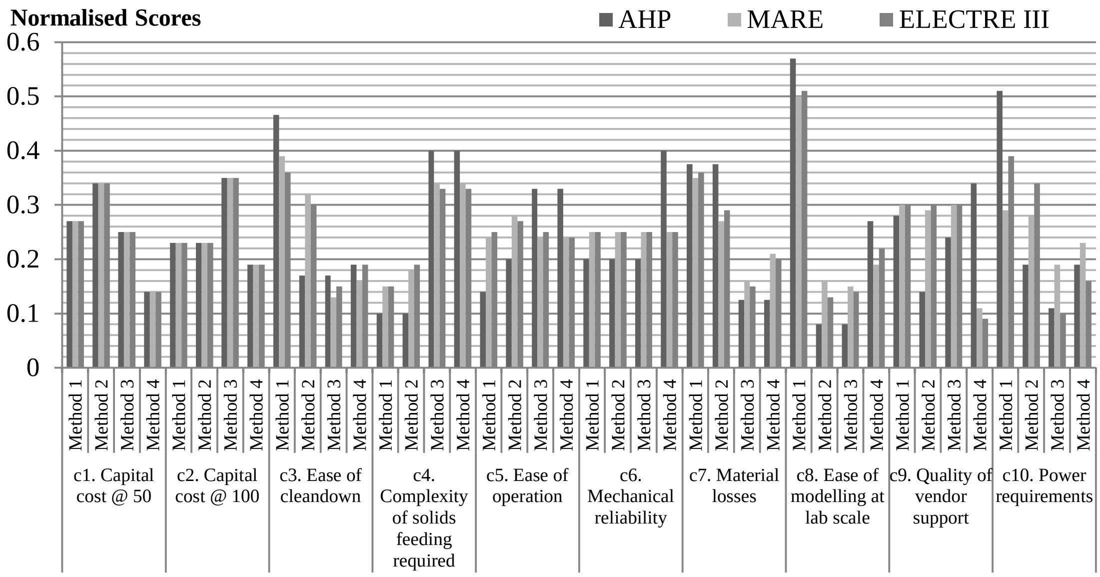

Figure 8 Comparison of the three analyses alternative scores

4.3 Results

Figures 9, 10 and 11 show the respective results of AHP, MARE and ELECTRE III. All three analyses recommended methods 1 and 4 over methods 2 and 3. However, table 3 shows that the orders of the results clearly differ. ELECTRE III was unable to provide a conclusive best result as the descending rank identified method 1 as the best alternative while the ascending rank identified method 4 as the best alternative. AHP clearly indicated that method 4 was the best alternative followed by methods 1 and 3. MARE identified method 1 as the best alternative but also showed that there was a high amount of uncertainty associated with method 4. In terms of the most likely value, method 4 was the second best alternative. However, the uncertainty range of method 4 indicated that it could be, in a worst case scenario, the lowest performing alternative. Therefore, method 2 may be a preferred second best alternative as its uncertainty range is much smaller.

Table 3 Comparison of the three analyses

	1st	2nd	3rd	4th
AHP	Method 4	Method 1	Method 3	Method 2
MARE (Most likely value)	Method 1	Method 4	Method 2	Method 3
ELECTRE III	Method 1, Method 4		Method 2	Method 3

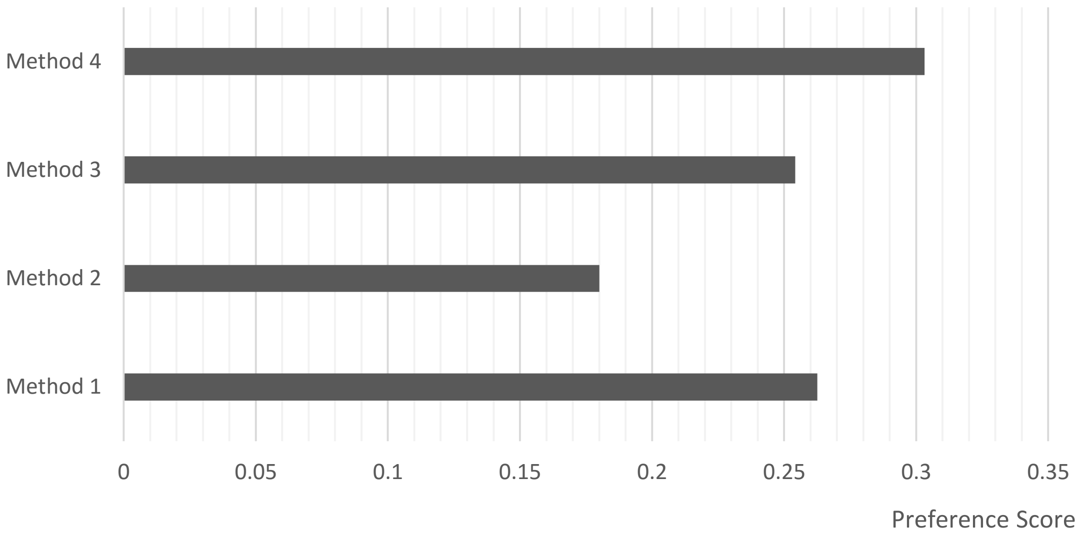

Figure 9 AHP Results for the FFIC Case Study

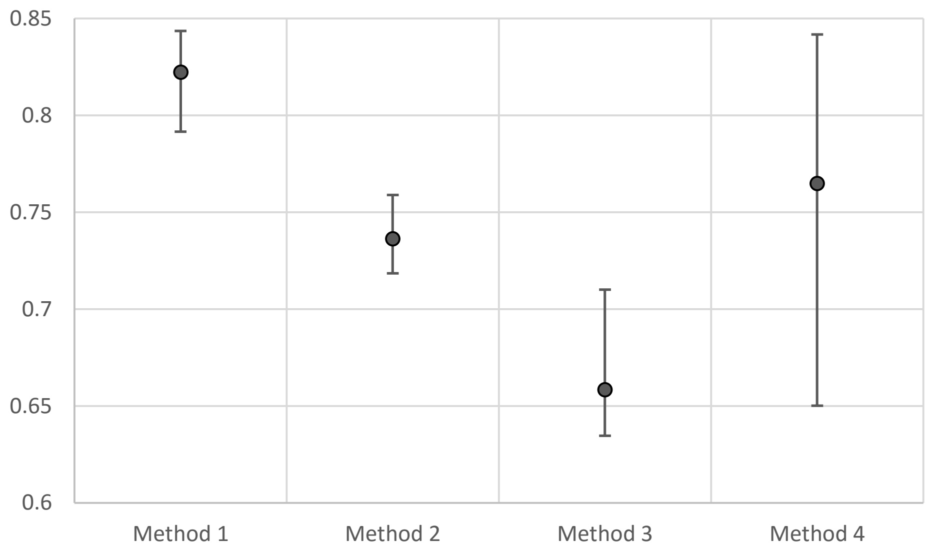

Figure 10 MARE Results for the FFIC Case Study

	Descending Rank		Ascending Rank		Final Rank	
1st	Method 1		Method 4		Method 1	Method 4
2nd	Method 4		Method 1		Method 2	
3rd	Method 2	Method 3	Method 2		Method 3	
4th			Method 3			

Figure 11 ELECTRE III Results for the FFIC Case Study

4.4 Post analysis interview

Post analyses, the decision-maker reviewed his experiences and discussed the results. On reflection, the decision-maker preferred the MARE tool for its ability to handle uncertainty, for the unique way it supports minimum and maximum values in the quantitative input and for the visualisation of the output. In particular he liked how MARE returned "confidence intervals" as an output. He explained that "the output represents reality and therefore I think MARE is good for displaying the real situation". He also stated that "the catch is [with MARE that] you might end up with multiple potential decisions still". This statement refers to the fact that a choice still needs to be made in terms of which alternative to select as at times there are overlaps between the uncertainty ranges whilst in comparison, AHP and ELECTRE III provide a definitive result.

Considering AHP and ELECTRE III, the decision-maker favoured AHP due to "forcing direct comparisons" in terms of qualitative input. Furthermore, AHP is potentially the tool that can be implemented most quickly but "for a small number of parameters only". In terms of ELECTRE III, the decision-maker said he lacked confidence in the tool as he was "more nervous of the outputs as AHP and MARE was more clear".

Reflecting on the inconsistencies in the three analyses, the decision-maker observed how AHP placed considerable emphasis on a number of criteria weights and qualitative decision variables. After analysing the input in Figures 6 and 8, the decision-maker stated "MARE and ELECTRE III *are pretty consistent and are probably more representative and accurate"*.

From the outputs of the analyses, the decision-maker further evaluated method 4 as it had been highly ranked even though from the results of MARE, it showed much greater uncertainty. The work undertaken was unable to reveal how achievable method 4 was so in the end Fujifilm Imaging Colorants Ltd chose to implement method 1.

5. Discussion

The FFIC case study demonstrated a decision problem with a significant number of criteria involved in making the decision. The size of the problem necessitated the decision-makers to consider a number of qualitative preferences which required a significant amount of time and effort. Figure 8 shows that a number of the inconsistencies in this case study occurred at the end of the decision-modelling process, i.e. the decision variables in respect to c10 ('power requirements'). These inconsistencies could be due to the tiredness and lower mental acuity of the decision-maker causing a lower level of attention due to the intricacies of the decision problem itself. Vohs et al. (2005) refers to this condition as decision fatigue.

Vohs et al. (2005) stated that "choice, to the extent that it requires greater decision-making among options, can become burdensome and ultimately counterproductive". They argue that making multiple choices requires effort, exhausts self resources and thus impairs self-regulation. They also stated that "the most advanced form of [decision-making] involves weighing information about currently available options to select the option that seems most promising". This statement clearly describes the task of using MCDM. Through a series of experiments with undergraduate students, Vohs et al. (2005) found that "self-regulation was poorer among those who had made choices than among those who had not". Therefore it is plausible that in a larger decision problem (such as the FFIC case study) inconsistencies could occur at the end of the analysis due to prolonged attention and mental effort causing decision fatigue.

Another explanation for the high amount of variation associated with the least important criterion in all three analyses, c10 ('power requirements'), is that the decision-maker may perceive the selection to have little impact on the decision itself. However, to gather accurate recommendations from a structured decision analysis, it is vital that decision-makers select all their preferences carefully.

Table 4 Scale of the AHP Method (Saaty, 1980)

Scale	Verbal Expression	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favour one activity over another.
5	Strong importance	Experience and judgment strongly favour one activity over another.
7	Very strong importance	An activity is favoured very strongly over another.
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
The values of 2, 4, 6 and 8 are compromises between the previous definitions.		

Nevertheless, it is clear from Figures 6 and 8 that the AHP module exhibited the highest number of inconsistent selections with the majority of values showing greater or lower emphasis than the MARE and ELECTRE III analyses. This occurred despite the fact that all of the decision-makers' pairwise comparisons were mathematically consistent. This was confirmed by the consistency ratio being below 0.1 in all of the pairwise comparison sets (Saaty, 1980). Therefore, either the decision-makers' knowingly placed emphasis on their preferences or there are inaccuracies in the 1-9 scale and definitions proposed by Saaty (1980). Table 4, which shows Saaty's 1-9 scale, suggests that there is a relationship with equal dispersion between the scale values. Consequently, the control developed for pairwise comparison input in the AHP tool was a slider bar with equal distances between each scale selection. However, Salo and Hämäläinen (1997) identified that there is an uneven dispersion of values in Saaty's AHP selection scale. They concluded that the difference in selecting between the scale of 1 and 2 is 15 times greater than the difference in selecting between the scale of 8 and 9. This indicates that Saaty's scale (Saaty, 1980) is accountable for the overemphasised criteria weights and decision variables in the case study.

One solutuion to correct the slider bar used in ChemDecide would be to modify the spread of selections to match the actual range of preferences in AHP. Another solution, proposed by Salo and Hämäläinen (1997), is to use balanced scales, for example the scale values of 1, 1.22, 1.5, 1.86, 2.33, 3, 4, 5.67, 9 provides the balanced values of 1-9. These scales would ensure an even dispersion of preferences that will subsequently provide uniform selections.

6. Conclusions

Equipment selection is an important activity for manufacturing companies as selecting the wrong equipment can be costly with respect to product quality, production time, production rate and resource allocation. It has been suggested that an effective and efficient Multi-Criteria Decision-Making (MCDM) tool should be used to address equipment selection problems. However, many different MCDM techniques have emerged which can yield different results when applied to an identical problem. In this context, this study examines the compatibility of three different MCDM methods with an equipment selection problem. A software framework which incorporates Analytical Hierarchy Process (AHP), Multi-Attribute Range Evaluations (MARE) and ELimination Et Choix Traduisant la REalité trois (ELECTRE III) was developed and distributed to a technology manager at Fujifilm Imaging

Colorants Ltd (FFIC). The manager, within a team of nine people, examined an equipment selection problem in the early stages of a chemical manufacturing process. A number of conclusions can be drawn:

- A high number of criteria (10) required 45 pairwise comparisons from the decision-maker to establish criteria weights using AHP. MARE and ELECTRE III only required 10 selections to determine the criteria weights meaning the AHP analysis was comparatively time-consuming and cumbersome.
- The normalised weights and scores of the three analyses were inconsistent with AHP showing the highest variation (Figures 6 and 8). This was most likely attributed to inaccuracies with AHP's selection scale, decision fatigue and the decision-makers' perception that criteria with a low weight have little impact on the decision results.
- There were significant differences in the results of the three methods. ELECTRE III was unable to provide a conclusive result, indicating that methods 1 and 4 were joint best solutions. AHP indicated that method 4 was the best option while MARE identified that method 1 was best. However, MARE also identified that there was a high amount of uncertainty associated with method 4 and in a worst case scenario, method 4 could be the lowest performing alternative.
- The decision-maker preferred the MARE method for its ability to handle uncertainty, for the unique way it supports minimum and maximum values in the quantitative input and for the visualisation of the output. He explained that "the output represents reality and therefore I think MARE is good for displaying the real situation".

The comparison of the different MCDM methods directly influenced Fujifilm Imaging Colorants Ltd to make an informed decision to select a piece of equipment to mix a substance in the early stages of process development. By going through this process the team of industrial professionals became more knowledgeable about their decision and the uncertainty associated with each equipment option, directing them to further evaluate one equipment option before implementing another. The results however clearly show that there is a risk in following the results of one particular MCDM method. Therefore, if time permits, it is advisable to address an equipment selection problem using multiple decision-making methods. However, if time is a constraint then the results indicate that MARE was the most effective method in providing accurate representations of the decision-maker's preferences and comprehending the uncertainty present. These findings should assist manufacturing companies in selecting a compatible decision-making methodology for equipment selection problems which will potentially lead to higher product quality, shorter production times and better resource allocation. The findings of this study should also encourage industrial professionals from manufacturing companies to explore and compare other MCDM methods such as ANP, TOPSIS and PROMETHEE, in order to examine the compatibility of a wider range of MCDM methods with equipment selection decision problems. Hopefully this will become more feasible in the future with novel tools such as the Multi-Criteria Decision Aiding package for R (Meyer, et al., 2015) which facilitates the use of multiple MCDM methods in one software package. Further case studies are required to test and validate the theories and recommendations presented in this paper as only one equipment selection problem was evaluated by one team of industrial professionals. A second equipment selection case study has already been developed in conjunction with GlaxoSmithKline and will be published in the near future.

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