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Decision-making methods in engineering design: a designer-oriented approach

Métodos para la toma de decisiones en el diseño de ingenieria de un punto de vista orientado al diseñador

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Abstract: The use of decisional methods for the solution of engineering design problems has to be tackled on a “human” viewpoint. Hence, fundamental is the identification of design issues and needs that become a designer oriented viewpoint. Decision-based methods are systematically classified in MCDM methods, Structured Design methods and Problem Structuring methods. The results are organised in order to provide a first reference for the designer in a preliminary selection of decision-based methods. The paper shows the heterogeneous use of decision-based methods, traditionally expected to solve only some specific design problems, which have been used also in different design contexts. Moreover, several design issues, which emerged from the review process, have been pointed out and discussed accordingly. This review provided useful results for the enlargement of the state of the art on Decision Based Design methods in engineering design contexts.

Keywords: Multi-criteria Decision Making; Decision Based Design methods; Engineering design.

Resumen: El uso de métodos decisionales para la solución de problemas de diseño de ingeniería debe abordarse en un punto de vista "humano". Por lo tanto, lo fundamental es la identificac ón de problemas y necesidades de diseño, que se convierten en un punto de vista orientado al diseñador.

Los métodos basados en la decisión se clasifican sistemáticamente en métodos MCDM, Métodos de Diseño Estructurado y Métodos de Estructuración de Problemas. Los resultados están organizados para ofrecer una primera referencia al diseñador en una selección preliminar de métodos basados en la decisión. El documento muestra el uso heterogéneo de los métodos basados en decisiones, que tradicionalmente se espera que resuelvan algunos otros problemas de diseño específicos, que también se han usado en diferentes contextos de diseño. Además, varios problemas de diseño, que surgieron durante el proceso de revisión, se han señalado y discutido en consecuencia. De esta revisión surgieron resultados útiles para la ampliación del estado del arte en los métodos de diseño basado en decisiones en un contexto de diseño de ingeniería.

Palabras clave: Toma de decisiones multicriterio; Métodos de diseño basados en decisiones; Diseño de ingeniería

1. INTRODUCTION

Engineering design and problem solving are so strictly connected that, in the years, engineering design has been also defined as a rational problem-solving process (Simon 1969 as in Reich 2013).

On the other hand, some critical studies claim that problem solving does not exhaust the design process (Dorst 2006; Hatchuel 2001; Hatchuel et al. 2013). In the literature (as an example Rajan 1997), design has been also conceived as a process made of a series of decisions. To this purpose, Allen and Mistree (1997) distinguish between two kinds of decisions, the selection decision (i.e. “either- or”) and the compromise (a trade-off). It is widely recognised, however, that the presence of conflicting requirements, industrial, technical and economic constraints, and uncertain data make the product design a challenging task, which involves a multi-criteria decision-based approach in several steps within the design process.

Decision-Based Design (DBD) methods are useful for reducing the multiplicity of attributes, which is a typical aspect of the engineering design problems (Krishnamurty 2006). In particular, in the formulation of a decision model, the attribute space, the classification of the design scenario, the significance of the selection of a preference assessment method are fundamental issues to be assessed properly. Moreover, to gain accurate results, suitable decision rules have to be chosen accordingly (Saari 2006).

DBD methods have been developed over the years, showing capabilities to support designers in solving design problems.

Anyhow, several decision-based methods remain largely unexplored in industry. As an example Salonen and Perttula (2005), searching for decision support applications on concept selection in Finnish industries, observe that only a little use of concept selection methods is made. In particular, one to four companies uses structured design methods, as PuCC (Pugh 1981), Rating matrices or AHP. Yang (2007) remarks that a wide part of designers, for instance, are familiar to non-structured methods, (e.g. brainstorming, benchmarking and need finding), but rarely with structured methods as Systematic Design (Pahl and Beitz 2006), Axiomatic Design (Suh 2001), TRIZ (Altshuller 1999), and Pugh's concept selection (Pugh 1981). Moreover, designers are seldom motivated to use decision-based methods in their daily routine and prefer tested procedures and experience-based approaches.

As described in Renzi et al 2017, several researchers have been investigating the issues laying at the basis of this hesitancy in the industrial adoption of such methods. The reasons lay on the fact that designers usually rely on their experience to solve the most frequent design problems. Hence they use specific decisional design methods exclusively to solve less frequent, new or complex design problems (Eder 1998). Most part of the decision-based methods also have to be adapted to fit specific design problems and companies, and the knowledge transfer to the industrial context often requires a deep transformation of companies' practices and habits (Reich 2010).

Nevertheless, the importance of integrating decision-based design methods within an enterprise driven background has been already remarked (Chen et al 2013). To this aim, several literature reviews focus on decision support applications related to industrial cases studies within the engineering design field. Krishnan and Ulrich 2001 adopt a decision-making perspective for broadly describing the product development process. The focus is on answering questions rising from decision problems, rising from concrete needs of the designer.

In Agrell 1994, a concurrent engineering viewpoint is adopted to describe the product design process. A specific compromise-programming algorithm is proposed, as a multi-criteria tool for designing manufacturability applications. Deng et al 2010 introduce an intelligent multi-criteria decision based method, which is characterized by multiple functions and limited testing experiences. It consists of three techniques for selecting relevant design factors, rapidly meeting the specifications and overall estimating the investigated prototypes. In Montagna 2011, a Hybrid Approach is proposed, in which an analyst is intended to guide the designer through the decisions involved in the product development process.

More to the point, a typical problem affecting practitioners in small and medium enterprises consists in the reluctance in adopting new techniques and approaches in their standards. This problem, which is mainly due to internal structure inertia or to a lack of dedicated (human) resources, often causes a contingent delay in their innovation level.

On the other side, most of the already available solutions, which are related to the identification of engineering and marketing requirements within the conceptual design process, are prerogative of large enterprises. This is mainly due to high cost in terms of time consumption, knowledge required, human resources, and technologies involved in their implementation (Jetter 2006).

Usually, designers who search for the most suitable Decision Based Design methods, for solving a specific problem, can follow two paths. They can either rely on their expertise as designers and decision makers, and/or they can tackle a huge amount of literature references, to catch, by analogy, the technique that best fits the proposed design problem to be solved.

Hence, the present work aims to provide a common background for designers and decision makers, in the research related to the use of Decision-Based Design methods for engineering design problems. To this purpose, this work proposes matches between the design problems -correlated to both the designers' needs and the consumer's needs- and the decision-based methods, adopting a human- oriented perspective.

As a second purpose, this research aims at mapping the distribution of the literature related to Decision Based Design methods dedicated to the solution of engineering design problems. This is the result of the review of cases studies reported in the literature, which treat and solve specific design problems by means of DBD methods. This is aimed to provide the reader with a "compass" in the choice of the proper decision based design method, to solve a specific design problem

This review is structured as follows. Section 2 describes the method followed throughout the review process. In particular, the review method starts from the definition of the keywords, which have been used for carrying out the search process. To this aim, starting from the definition of the engineering design process, the designer's needs have been assessed. Moreover, a taxonomy of the most used state-of-the-art DBD methods is proposed. As a first result, two sets of keywords, related to the designer's needs and the DBD methods, have been built for the search process. Section 3 describes some recurrent key issues that emerged from the literature review. In particular the management of the uncertainties in the early design phases, the description of the consumers' and designers' preferences, and some peculiarities of the pairwise comparison technique are tackled and described in this section. In Section 4, the use of DBD methods for solving engineering design problems is quantitatively described, based on the results of the literature search process. A conclusive section closes the paper.

2. REVIEW METHOD

The review method is based on the assumption that the design process is made of several steps, involving more than one decision-based techniques. Starting from a common definition of the engineering design process a relation between design steps and design needs is proposed, through the main phases of the design process. Key words for the search process came out from the analysis of the designer's needs and of the decision based methods, involved in the problem solving.

A search process has been performed trough out the scientific literature, to find the most used techniques for solving each of the core problems above mentioned, within each design phase. The core problems, deriving from the designer's needs individuated, have been used as keywords for the search process.

2.1. ENGINEERING DESIGN PROCESS

Several descriptions of the engineering design process workflow have been proposed in the literature. Among them, some are worth to be recalled since are based on a very common framework: Asimow (1962), Pahl and Beitz (1996), Dieter and Schmidt (2008), Ulrich and Eppinger (2008).

The approach adopted in the perspective of the present review is the systematic approach proposed by Pahl and Beitz (1996). Accordingly, four steps lay at the basis of the product design process: the design planning, the conceptual design, the embodiment design and the detail design (Figure 1).

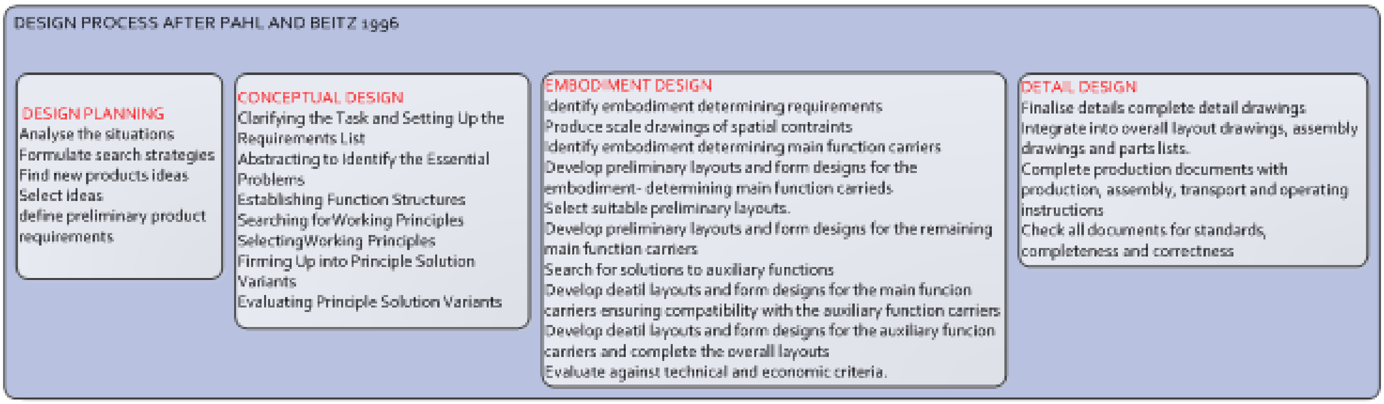


FIGURE 1 PRODUCT DESIGN PROCESS AFTER PAHL AND BEITZ (1996)

2.2. DESIGNER'S NEEDS

According to many authors, the engineering design process has to start from the needs of designers, as is continuously remarked in the literature (Krishnan and Ulrich 2001, Dieter and Schmidt 2008, Montagna 2011).

Actually, the needs of the designer are mainly due to external causes. In particular, there are industrial reasons that guide the choice for improving the quality of the product, in order to fulfil specific design standards. Moreover, there are environmental needs, leading to sustainable design for the product. The company's needs lay at the basis of product design changes oriented to the reduction of time to market. In addition, the customer's needs aim at providing modifications to the product in order to solve failure problems or increase the lifecycle of the product. Therefore, the designer has to solve the design problems considering all the specifications required by the industrial/economic entities, the environmental context, the company and the customers (Figure 2).

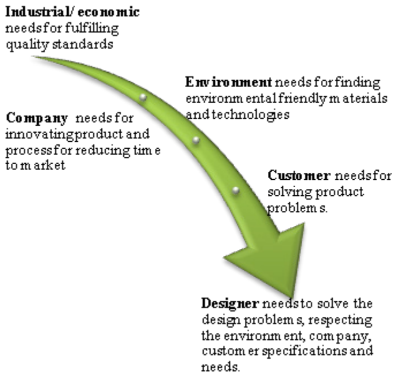


FIGURE 2 FACTORS INFLUENCING THE NEEDS OF THE DESIGNER.

The main assumption of the method is that the capability of a designer to solve a design problem depends on his aptitude in clearly recognizing the needs to be fulfilled, i.e. the problems to be solved. The specific needs rising from each phase of the product design process, the designer is required to answer to specific problems and questions within each phase of the design process. Figure 3 describes the macro steps addressed during the review process.

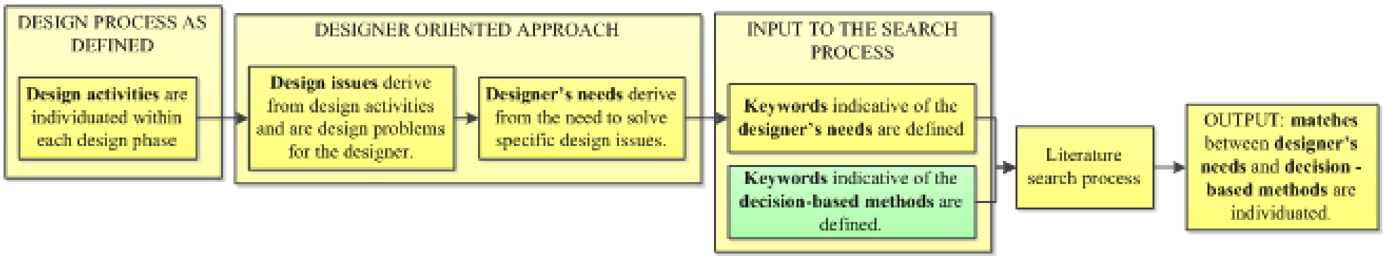


FIGURE 3 PROCESS ADOPTED FOR INDIVIDUATING THE DESIGNER'S NEEDS AND THE CORRESPONDING KEYWORDS FOR THE REVIEW SEARCH PROCESS.

First the design activities deriving from the engineering design process have been individuated for each design phase. Therefore, the same activities have been translated in design issues, in order to finally define the designer's needs. Table 1 proposes a relation between every phase of the design process with corresponding designer's activities and issues. The most frequent are: tackling uncertainties in data and information, translating the customer's needs into specifications for the product, aggregating the preferences of the decision makers, selecting design alternatives, materials or industrial equipment for carrying out a specific manufacturing process.

Table 1 activities and issues involved in the design phases.

Planning phase	to cope with uncertainties in data or information
	to individuate problem causes
	to specify the product requirements
	to translate the customer's needs into specifications for the product.
Conceptual design phase	the aggregation of preferences of the decision makers
	the selection of alternatives
Embodiment hase	search for a compromise design for gaining the complete architecture of the assembly
Detail design	selection of material and industrial equipment.

Hence, the designer's needs that have to be fulfilled to carry out the product design process have been listed as decision questions arising within a specific design phase.

In the planning phase the designer's needs are: How to handle uncertain data, for reaching efficient solutions? How to plan complexity in unstructured problems if the objectives are unclear? How to handle diagnostic and find problems roots? Which requirements must the product satisfy? What do customers expect from this product?

In the conceptual design phase the designer has to ask himself: How to find a mathematical expression for the DMs' preferences? How to aggregate the preferences of the DMs in one? How to describe the indifference threshold for describing the preferences of the alternatives? How to handle verbal judgments for preferences? How to select/ rank the alternatives?

In the embodiment design phase, the questions arising are:

How to select the best solution in constrained problems? How to handle compromises between solutions?

Finally, in the detail design phase the needs to be fulfilled are: How to select the most suitable material/ manufacturing process/industrial equipment?

According to the needs individuated, keywords related to the needs of the designer have been defined. In particular, for the planning phase, the keywords are related to the ways in which uncertainty can be managed in early design problems and the search for problem causes. In the conceptual design phase, the keywords are related to the preference description for the selection of design alternatives. The keywords related to the embodiment design phase claim the search for a compromise solution and the evaluation of the performance of the whole product design. Finally, in the detail design, keywords are related to the selection of the most suitable material or the industrial equipment or the best manufacturing process. Other keywords have been proposed as indicative for the decision-based methods.

Thus, a combination of keywords have been used in the search process, showing as output the possible match between the designer's needs and the decision-based methods.

The detailed research process has been depicted in Figure 4.

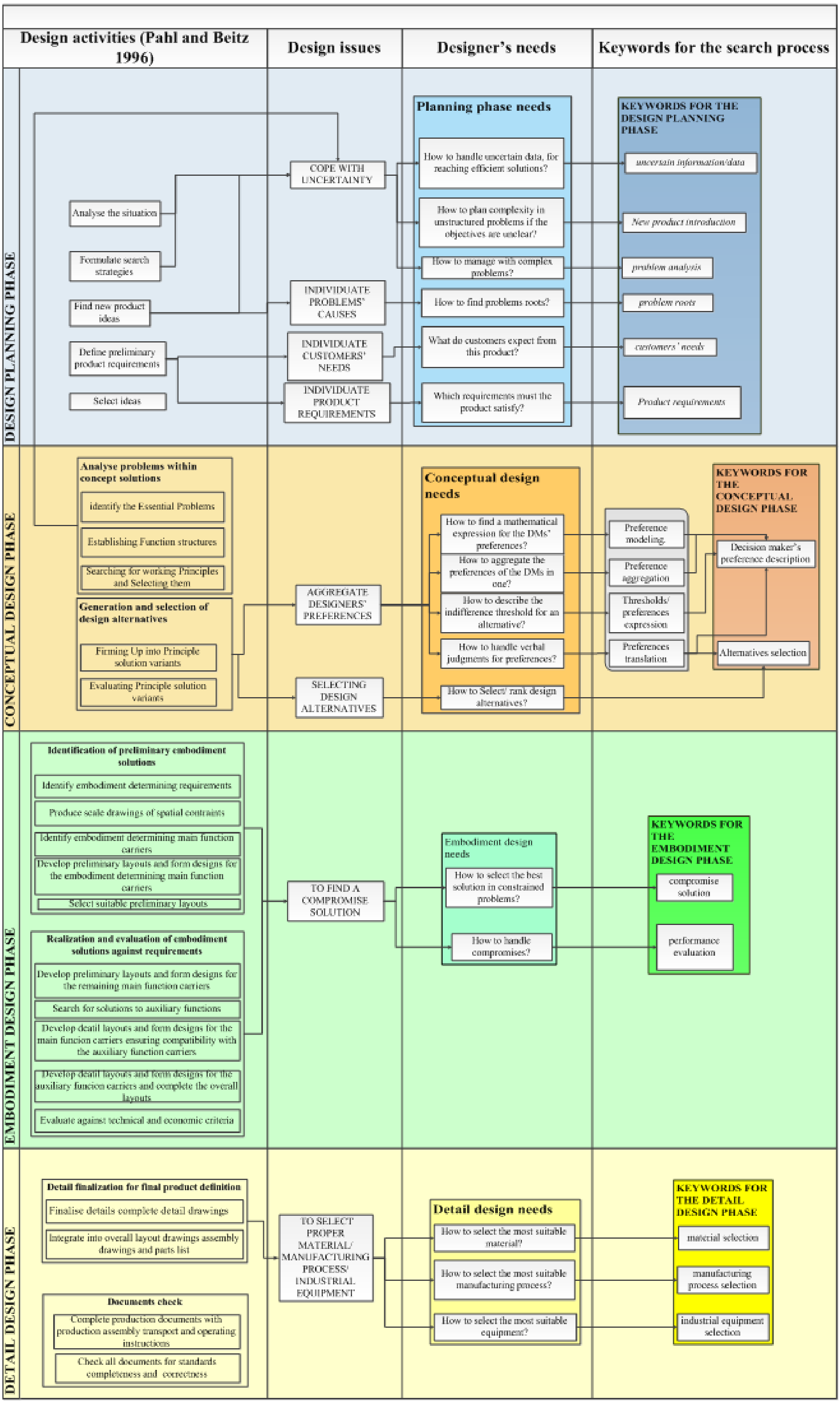


FIGURE 4 DESIGNER'S NEEDS THROUGH THE MAIN PHASES OF THE DESIGN PROCESS.

2.3. DECISIONAL METHODS AND TECHNIQUES

Three main groups of decision-making techniques can be proposed as useful tools for solving several design problems: the MCDM methods, the Structured Design Methods and the Problem Structuring Methods. Even if these three families of methods are well known by decision-making scholars, this representation is novel in the literature, and therefore has been proposed in Figure 5, for the sake of clarity.

According to a traditional taxonomy, as the one introduced by Belton and Stewart (2002) for the description of MCDM techniques and reported in Fig 5, the MCDM techniques can be grouped into two additional sub-areas, the Multi Attribute (MADM) and the Multi Objective (MODM) decision-making methods. The former deal with a finite number of alternatives and a discrete solution space, while the latter handle a continue solution space and search within an infinite (and unknown) set of solutions. Among MADM are the Value Measurement methods and the Outranking approaches, while the Goal, Aspiration and Reference level models belong to the MODM techniques.

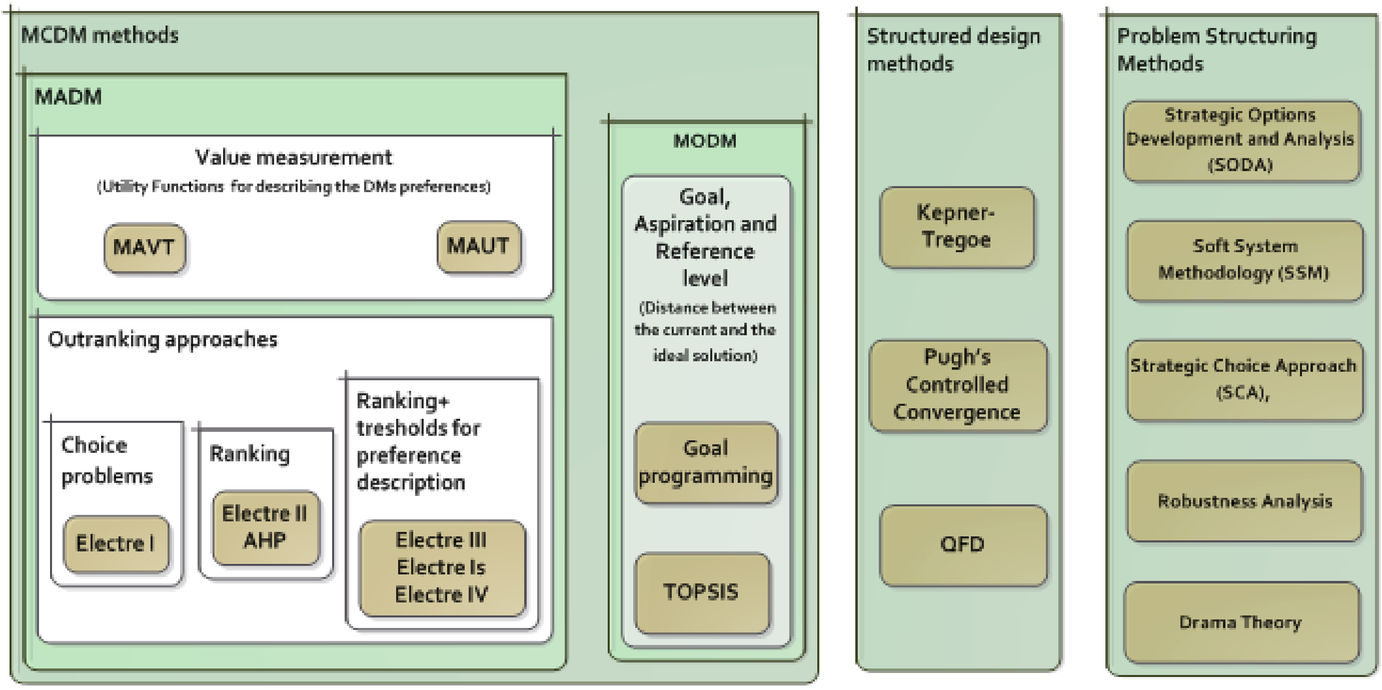


FIGURE 5 TAXONOMY OF DECISION SUPPORT TECHNIQUES FOR SOLVING ENGINEERING DESIGN DECISION PROBLEMS.

2.3.1. MULTICRITERIA DECISION MAKING METHODS

In the following section, multicriteria decision problems have been analysed under the MCDM techniques viewpoint. In particular, MCDM techniques are briefly described, enlightening some peculiarities that will be considered in more detail in the second part of this review. Following the classification of Belton and Stewart 2002, the MCDM methods can be subdivided into the multi attribute and the multi objective decision-making problems. The former search for a discrete set of solutions, in which the alternatives are predefined. The latter work with a continuous set of solutions, which are not defined before.

Multi attribute decision-making methods include the Value measurement methods, the Outranking methods and the Distance-based methods. In the following subsections, the most salient characteristics will be outlined.

VALUE AND UTILITY BASED METHODS

Value measurement problems are tackled by means of multi attribute techniques considering the value and the utility theory. In particular, MAUT and MAVT are used to solve problems involving multiple conflicting objectives, within a discrete set of alternatives. The former employs a utility function for preference representation, in order to evaluate a trade-off between attributes over the attributes domain (Malak et al 2009). Besides utility is a term used for describing a selection criterion in presence of uncertainty The latter involves a value function for representing the preferences of the decision makers, but while the Utility function includes the risk preferences of the decision maker, the Value function does not.

Von Neumann and Morgenstern (1954) and Savage (1954) introduce MAUT, which has been further developed at the end of the 20th with Keeny and Raiffa (1993). MAUT technique is able to formally describe perspective and evaluations to build a decision-making process: the goal is to find a simple expression describing the decision maker's preferences (Zavadskas et al 2008).

Similarly, Keeney and Lilien (1987) describe MAVT approach as a three steps-method, namely: specification of product attributes for a given customer requirement, identification of an evaluation model, which gives shape to the multi-attribute value function; the assessment of the value judgment which calibrates the value function on the customer's requirements. The overall value function, which is the sum of the weighted scores for a given attribute, represents the trend of the alternatives, from the nadir to the ideal one. MAVT involves four steps essentially, to be carried out, namely: the definition of the alternatives, the selection and definition of criteria, the assessment of scores for each alternative, in terms of each criterion. Finally, the ranking of the alternatives is performed, by applying a value function U to all criteria scores.

The first three steps are the same as in most MCA methods. Step 4 is specific for MAVT. In the definition of the MAVT it is assumed that the preferences of the decision maker in every decision problem are represented by a real value function U. This value function aggregated the criteria for each alternative aj (j=1..M) the criteria ci (i=1..N) which are under consideration by the decision maker. The problem using the general form of the function U can be formulated as the best alternative is a, for which the value of U(c1(a), c2(a),…, cn(a))=max j=1,…M U(c1(aj), c2(aj),…, cn(aj)).

The functions Ui in the additive form of the MAVT can be used to transform the different measurement scales of the criteria to an identical scale and are called partial value functions. This form, however, will only be appropriate if the decision−maker's preference structure satisfies the mutual preference independence condition.

MAVT deals with the real world complexity by allowing attributes to interact with each other in other than a simple, additive fashion. Unlike the simplified additive form, it does not assume mutual independence of preferences, even if interactions can be modelled by means of the value function model.

Thurston 2006 provides a useful description of costs and benefits of utility-based methods in engineering design, according to each design stage. One of the main limitations claimed is that the use of utility functions is only able to reveal inconsistencies of prior choices, without influencing the customers preferences. On the other hand, utility based methods are capable to provide separation of the true objectives from the unnecessary ones, to define true trade-off ranges, avoiding the biases, inconsistencies and paradoxes in customers.

In the creative phase of the generation of design alternatives, on one hand, the utility based design methods are not able to replace creativity, nor engineering expertise. On the other hand, they allow the designer to think in functions rather than in form. Besides they provide an initial filter for material, configuration, manufacturing options, according to attributes and range definition.

In the phase of design analysis, even if the utility-based methods are not able to define analytic constraint equations, they are capable to indicate the relevancy of each analytic equation. In the trade off analysis evaluation, they cannot determine which trade-offs are technically feasible. On the other side they are able to rank orders preliminary alternatives. Concerning the management of the uncertainties, they are not able to remove uncertainties, but they are capable to model them and to include the effects of uncertainty on rank order of alternatives, avoids irrationality and understand if there is the need of gaining more information.

According to group decision making, while not resolving the Arrow's impossibility theorem, they provides a framework for gaining preference information from individuals and group.

Besides they communicate preference information to team members, brake decision problems into components, on which consensus can be reached.

Concerning utility-based methods, despite its mathematical consistency, MAUT is often used as an auxiliary method for including the decision maker's preferences, instead of as a decision support alone (Fernandez et al 2005). Thus, in practical applications, it is combined in hybrid forms with outranking or distance based methods.

Even if MAUT is largely investigated within product design research (e.g. Hazelrigg 1998, Thurston 2001, Fernandez et al 2005), someone considers it too complex for practical decision-making (Holt and Barnes 2010).

OUTRANKING APPROACHES

Outranking approaches determine the alternative that better fits given constraints (goals and criteria), by means of a pairwise comparison of the alternatives, against each criterion. The first outranking method, ELECTRE I (ELimination Et Choix Traduisant la REalité), was proposed by Roy (1968). Later, several derived methods were developed, as, the ELECTRE-derived family (ELECTRE I, II, III, IV, Is, Tri), ORESTE, PROMETHEE. The ELECTRE methods are based on preference modelling and aim at generating priorities, describing partial preferences and choosing a set of promising actions. Vincke (1992) focuses on the differences between the Electre Family methods, remarking that the Electre I is designed principally for choice problems, in order to find a subset of candidate actions, in which the best compromise is surely determined. Out of this subset, at least one of the candidates outranks each action, by means of an outranking relation. Electre II instead, is intended for ranking actions from best to worst, while Electre III, is for ranking actions too, but introduces thresholds, for describing preference, indifference and veto within the decisional actions. Moreover, the latter method involves a valued outranking relation, for reducing sensitivity to changes in the data and parameters involved.

As observed by Hatami-Marbini and Tavana (2011), an advantage of the Outranking Methods is their ability to maintain the ordinal scale without adapting the original scale into an abstract one (as it happens for AHP, TOPSIS, MAUT, etc.). However, an inconvenient drawback is the need for a precise value of criteria weights and performance rating, in order to manage uncertainty or for handling the linguistic nature of the judgments of the decision makers. As noticed by Bouyssou (2001), in order to give a numerical value to the weights, it may be useful to imagine plausible alternatives, combining credible evaluations on various attributes.

De Boer et al (1998) provide a literature review of the main applications of ELECTRE I concerning the supplier selection problem, recommending this method throughout the initial phase of the decision process. In particular, they focus on the aptitude of ELECTRE I to consider uncertainties, even if ELECTRE III is more specialized to it. ELECTRE IV is the only Electre method for ranking actions without using the relative criteria importance coefficients

In this perspective, as Roy is the founder of the outranking techniques in Europe, T.L. Saaty, who first introduced the Analytic Hierarchy Process (AHP), is the founder of the outranking approaches in America (Saaty, 1980).

In AHP, four phases can be distinguished. First a top-down evaluation of the alternatives is made, then a pairwise comparison, with a 9-points fundamental semantic scale is implemented, a bottom-up hierarchical reassembly, with priorities evaluation and consistency indices evaluation is realized, finall , a sensitivity analysis is done.

Even if AHP is a valid technique for evaluating alternatives, it has several faults, as for example, the lack of a theoretical framework for modelling the hierarchy of decision problems, or the use of subjective judgments in making pair wise comparisons (Zahedi 1986).

However, in several problems, hierarchical structure is not able to describe completely interactions and interdependencies between attributes, in which higher-level criteria strictly depend on lower levels. In this case, Saaty's ANP (Analytic Network Process) technique should be used (Saaty 2004). In fact, ANP is able to model dependencies between higher and lower levels of the criteria, thus providing a more realistic description of the problem. Thus, a network representation is more suitable for describing this kind of problems. In PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) is one of the most recent MADM methods. Initially introduced by Brans and Vincke (1985) and Brans et al (1986). PROMETHEE is used to rank a finite set of alternative actions, in a simpler way in comparison to the other MCDA methods. In Macharis et al 2004, a comparison between PROMETHEE and AHP is carried out, in order to enlighten the advantages of the latter that can be used to enhance the former. In particular, a number of useful AHP features are considered regarding the design of the decision-making hierarchy (ordering of goals, sub-goals, dimensions, criteria,…) and the weights definition

MULTI-OBJECTIVE DECISION MAKING METHODS

The establishment of goal or aspiration level for each objective can be reached by means of techniques individuating the ideal solution. In particular, Goal Programming and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) are distance-based methods.

In Goal Programming, two variables represent the positive and negative deviations of each objective, from the aspiration levels. Therefore, the solution satisfying all the given constraints, represents the compromise result, with the minimum distance between the attainment and the aspiration levels of the objectives (Kharrat et al 2011).

Originally introduced by Hwang and Yoon in 1981, TOPSIS helps decision makers organizing problems, ranking and selecting alternatives. It acts measuring the distances between both the positive and the negative ideal solutions and ranks the alternatives with respect to their relative closeness to them. According to Lotfi et al (2011), one of the most evident advantages of TOPSIS is the quick identification of the best alternative. In TOPSIS method, after the evaluation of the normalized and the weighted normalized decision matrices, the positive and the negative ideal solutions are evaluated, as extreme compromise solutions, for given benefit and cost criteria. Hence, the distance of each alternative from the positive ideal and negative ideal solution are measured, by means of the n-dimensional Euclidean distance. Therefore, the relative closeness to the ideal solutions is calculated and the alternatives can be ranked from the nearest to ideal solution to the farthest one.

2.3.2. STRUCTURED DESIGN METHODS

In the proposed classification of the decision support methods, the authors have defined the group of the structured design problems as the problems whose objectives are shared by all the stakeholders and that can be handled by means of problem solving techniques characterised by a systematic approach.

In this section, structured decision-making methods, as the Kepner- Tregoe (KT) method, (Kepner and Tregoe 1977) the Pugh's Controlled Convergence (PuCC) and the Quality Function Deployment (QFD) will be described. Nowadays, the problem solving procedure, laying at the basis of the KT method is efficiently adopted in strategic decision-making applications, for analysing and solving problems and for planning complex situations. In addition, KT selection matrices are employed- together with PuCC- in the conceptual design phase, to select product alternatives and are both based on the assessment of the alternatives against a set of criteria. Due to the different procedures that the above mentioned selection methods adopt for selecting concepts, Paryani (2007) differentiate them in qualitative (PuCC) and quantitative (KT matrices) selection methods. In fact, even if both methods assess positive and negative performance in the comparison process, the former leads to the possibility of generating hybrid solutions, while the latter assess the magnitude of this performance.

2.3.3. THE KEPNER-TREGOE METHOD

K-T METHOD: PROBLEM ANALYSIS AND STRATEGIC DECISION-MAKING

The K-T method is a decision aiding tool, made of four analyses purposes, namely: the Decision Analysis, the Problem Analysis, the Potential Problem Analysis, and the Strategic Planning.

The K-T method aims first at clearly stating the problem (Kepner and Tregoe 1977), making sure that all the people involved in, admit and recognize that a problem subsists. Then the problem is broken in parts, for enhancing analysis. Each problem is defined as a deviation from the effective objective and the KT method aims at discovering and evaluating the possible root causes. This evaluation process is carried out by means of four questions, (“What”, “Where”, “When” and “What kind of”) regarding the nature of the deviation and individuating the objects involved in the observed deviation.

Then, a boundary is provided for separating the areas in which the problem is present (“IS”), from the ones in which it is absent (“could be but IS NOT”). This is made in order to eliminate the intuitive -but incorrect- inferences about the problem. The “differences” and the “changes” for each of the previous questions are analysed, in order to understand the root causes, to focus on what is changed since the problem appeared. This investigation, which is often schematized in a table, can be considered as a core part of the KT systematic approach. Kepner and Tregoe (1965) remark that usually managers have to make decisions connected to problems that can be mostly solved by an accurate analysis, to determine relative problem causes. The correction of a cause is connected to the search for the most effective action for fixing the problem and minimizing both costs and disadvantages.

Regarding Strategic Planning, a five-phases- strategy model is individuated, for enhancing decision planning, in complex problems. In particular, the procedure starts gathering data concerning markets, competitors, technology and the internal/external environment, in which the organization would be required to operate. Therefore, some crucial strategic elements are defined, as the scope of product and services, the market and the business goal. At this step, the planning is implemented, by means of a project management tool, to achieve a detailed definition and a scheduling of each project

A further implementation of the strategy needs for iterative interventions, providing monitoring and modific - tions, in order to verify the validity of the assumption previously assessed.

CONCEPT SELECTION PROBLEMS BY MEANS OF KEPNER AND TREGOE MATRICES

Kepner and Tregoe (1965) stress on the importance of building a systematic approach to decision making, as well as for problems analysis. Some errors occurring within the searching procedure for design alternatives, may be corrected by a systematic decision making process. For example, managers tend to choose one alternative and, after they set the criteria, accordingly. In this way, however, the nature of the selected product sets the company's market objectives and not vice-versa.

Therefore, the first step of the decision making procedure, is the setting of the objectives, in which several data have to be gathered. In addition, objectives are classified in two categories: the "musts" and the "wants". The former are mandatory objectives, allowing for a first screening out of the weak alternatives. The latter express goals to be attained and desirability.

The second step is the weighing process, for establishing priorities among the "wants" objectives. First, a screening of the alternatives is done, according to the "musts" objectives. Each enduring alternatives is evaluated and ranked separately, against each of the "wants" criteria. Then alternatives are scored, by means of a ten-points scale.

The overall judgment for the alternatives is the product of the objectives weights and the scores of the alternatives.

The highest scored alternatives are thus considered separately, as they were operating in the real scenario, in order to evaluate the advantages and drawbacks of each candidate to solution.

One of the shortcoming for the K-T procedure of selection consists in the fact that, if the final scores between some candidate alternatives are similar, it could be not so clear which alternative should be chosen.

THE PUGH'S CONTROLLED CONVERGENCE

Regarding the formal structured design methods, the Pugh's Controlled Convergence (PuCC) is well worth investigating. The method is mainly used for selecting the product alternatives in the conceptual design phase. In this process, two phases can be distinguished, namely a screening and a scoring phase for the alternatives, which are characterized by the homonymous matrices (Ulrich and Eppinger 2008). In the former phase, which is characterized by the lack of a voting procedure, each concept is judged against each criterion as "better" (+), "equal" (0) or "worse" (-), with respect to a design given as a reference and called concept datum. This phase is followed by a second ranking level, in which the alternatives are classified, according to the previously defined priorities of the criteria. The process is iterative and the datum is to be changed in particular situations as, if some concepts exhibit a persistent strength or if they seem to be uniform. If a particular concept persists during iterations, this is taken as a datum concept and the matrix is re-run (Pugh 1981).

The PuCC method is useful also as a generator of new design alternatives, deriving from the selection of geometric specifications typical of two or more alternatives showing high scores for specific criteria

THE QUALITY FUNCTION DEPLOYMENT (QFD)

Krishnan and Ulrich (2001), in their review on decision-making in engineering design, describe the main decisions that should be included in the conceptual design phase of a product, as most of all, the assessment of product targets, which mainly consist in product requirements. In particular, the fact that the conceptual design phase have to start with the product requirements list, to be fully integrated with the customers' needs, is shared in literature (Pahl-Beitz 1996).

Several methods have been proposed, in literature, to elicit customer needs and turn them into product requirements. One of them, perhaps the most widespread, is the Quality Function Deployment (QFD), which aims at satisfying the customer demands, by relating them to goals for product characteristics.

Van de Poel (2007) points out benefits and limitations, linked to the application of the QFD to the product development process. He focuses in particular on some methodological occurring problems, namely: the dependence of the customers demand on the product, the difficulty of representing it with a linear additive value function and, most of all, the limitation- imposed by the Arrow's Impossibility Theorem- to convert customer's needs, from singular into collective demands.

Moreover, the author propose other QFD approaches to overcome these limitations, as the inclusion of Kano's model in QFD, market segmentation and demand modelling.

Yannou and Petiot (2005) provide the designer with a method for including customer's requirements in the conceptual design phase, by defining the "semantic part of the need", ranking the alternative prototypes according to their closeness to the ideal solution. The method is a combination of existing techniques related to disciplines of decision analysis, marketing and psychophysics, and each stage of the methodology is applied to the design of table glasses.

A study made on Brazilian Industries (Miguel 2003), showed that among over a hundred Brazilian companies, belonging to different fields, QFD resulted the most famous technique within automotive industry (even if the first to use it were the food companies). Nevertheless, almost 80 per cent of the practitioners confided not to use QFD in usual engineering design applications.

The recurrent reasons for this stance show up a low interest in the method and the tendency to use techniques entirely developed by the company. Moreover, the users denounced an inconvenience in handling the matrices representing customers' needs. This is especially because of the size of these matrices, usually on average of 25, for 31 quality characteristics.

On the other hand, the companies using QFD noticed an enhancement of the product development production and an increase of customers' satisfaction. The most used techniques in conjunction with QFD, within Brazilian companies, were seven-quality planning, seven tools for quality control, FMEA; instead, no use was made of AHP.

Cristiano et al (2000) as in Thia et al (2005) showed that QFD method is more used in American Industries, with resulting improvements in production, rather than in Japanese industries, even if the method has been first developed in Japan

From interviews carried out by the same authors, to Malaysian entrepreneurs, regarding the use of NPD tools and techniques, it appeared that most of industries use Brainstorming, FMEA and teaming. In addition, DOE and Beta testing are widespread among industrialists. Instead, QFD is seldom selected for practical applications, as it is declared time consuming and often needs a previous training. Even if the benefits of the method are known, the tool is often considered "tedious" in its procedure or too detailed for the scope. The exploratory study carried out by the authors, revealed also the features that make a tool more attractive than another, for industrial applications. According to the authors, a tool for NPD purposes is called to be user friendly, useful, time and money saving, flexible and popula .

Herrmann et al (2006), focusing on benefits and drawbacks of QFD gathered by several studies, remind its prerogative of improving design quality, fastening decision-making and recognizing customer needs. Moreover, it increases the companies' efficienc , by speeding up the production cycle and reducing misinterpretations and needs for changes. On the other side, QFD is accused to employ many resources leading to excessive retraining costs.

2.3.4. PROBLEM STRUCTURING METHODS

Decision-making is a complicated challenge since the early stages of the design phase, where many vague and indefinite requirements have to be elicited and accomplished and most of core decisions must be taken.

Pahl and Beitz (1996), (as in Dörner 1979), state that in a complex and uncertain problem neither all requirements are identified, nor all criteria are clear; moreover, the effect of a partial solution on the global one is not fully understood.

During the preliminary design phase, uncertainties are more frequent in the conceptual design phase rather than in the embodiment stage. Therefore, they state the importance of using Fuzzy set theory for managing vagueness, especially for prognostic uncertainties, as linguistic ranking may reduce the false perspective that a numerical scoring usually offers.

De Weck and Eckert (2007) catalogue recurrent uncertainties and suggest methods for modelling and incorporating them into system design. The authors, citing Earl et al (2005), individuate four categories of uncertainty in the design process: the known and the unknown uncertainties, the uncertainties in the data, the uncertainties in the description. While the known uncertainties can be well described and solved by comparison with previous cases, the unknown uncertainties cannot be estimated before. The uncertainties due to data deal with accuracy and quality of measures; the uncertainties due to the description of a system are inherent to the lack of clarity in the selection of the elements and the ambiguity of the description. According to the authors, the approach for modelling uncertainties in a design process starts with the methods of representing the system variables, depending on whether the variables are continuous or discrete. Examples of continuous variables could be the future prices of commodities and raw material, while the discrete variables involve the estimation of characteristics isolated events. In the first case the models for better describing uncertainties are diffusion (as the Geometric Brownian Motion) and lattice models, while in the second case the scenario planning models are used for representing the future as a set of defined scenarios

In the literature, ways for handling uncertainties during the planning phase of a general process are described by means of Problem Structuring Methods (PSM). Rosenhead (1989) denominates “soft-operational research techniques” those methods - as the Problem Structuring Methods- that, even if they are thought for different purposes, have a common structured frame, which (as described in Ackoff 1981) consists of five phases. The first phase consists on the prediction of the system appearance in the future, without any intervention on it. The second describes the characteristics that the system would have to fulfil and the objectives that have to be reached. The third phase consists in the description of the processes aimed at reducing the distance between the actual system and the desired one. The following step consists in searching for these processes. Finally, the resources needed to elaborate the action plan are found. Rosenhead and Mingers (2001) introduce the differences between their “alternative” viewpoint on problem structuring and the traditional operational research paradigm, in which, among the other things, the lack of an optimization process, the assumption of people as “active objects”, the acceptance of uncertainties and the aims of keeping options open are strongly evident.

These methods, which are categorized in five groups (Rosenhead and Mingers 2001), are told to be useful especially in meetings that lack of a formal agenda, or for wide-band problems, namely, non-pre-formulated problems. Mingers and Rosenhead (2004) affirm that these techniques tend to represent the situation so that it is clarified and converges on a problem to be solved.

The Problem Structuring Methods are, specifically: Strategic Options Development and Analysis (SODA), the Soft System Methodology (SSM), the Strategic Choice Approach (SCA), the Robustness Analysis and Drama Theory.

The first three are commonly applied, because their structure is suitable for several issues. Robustness Analysis has a particular focus on consideration of uncertainty about the future, while Drama Theory is useful for analysing conflicts and cooperation among parties, as it takes its foundations from the metagames and hypergames. The SODA method is suitable for identifying the problem, especially by means of cognitive maps, which are fit for guiding group discussions and leading to a possible set of actions to be taken, with the help of a facilitator.

Soft System Methodology (SSM) is helpful for redesigning systems, with the introduction of ideal type conceptual models. As remarked by Platt and Warwick, these technologies handle situations with active subjects and unclear objectives. SSM - first introduced by Checkland (1981) - includes several steps some of which are related to real world problems, namely the unstructured problem situation and the comparison of conceptual models with corresponding real situations. Others meet the definition of feasible changes to the actual unstructured situations. The core centre of the SSM method is the definition of the root of relevant systems by means of a checklist named “CATWOE”, consisting of six arguments to be analysed, namely: Customers, Actors, Transformation, Weltanschauung (or World view), Owner, Environmental constraints. These phases correspond to the steps to be tackled for analysing the situation and, therefore, solving the problem.

SSM belongs to a wider set of problems that is called “Soft-system” based modelling approaches. Clegg and Boardman (1996) have classified these methods in four groups, according to the application domains of the methods: the General System Theory, (Beer), the Soft System Methodology (Checkland), the Conceptual Mapping (Eden) and the Boardman Soft Systems Method (Boardman).

In their work, Clegg and Boardman (1996) apply the SWOT methodology to enlighten the Strengths, Weaknesses, Opportunities and Threats of the Soft Approaches, declaring as a strength the fact that the methods are people and process-phase oriented, and counting as a weakness the lack of a formal and structured approach and a possible suspicion of academic approaches by the industry. The goal carried out by the authors is the effort to improve the soft systems based modelling approach in a more rational way, without losing any of its strengths.

By means of the Strategic Choice Approach (SCA), Friend (1989) emphasizes the need of managing uncertainties in a strategic way. In fact, any decision maker, who has to tackle a complex problem (as the design process usually is), tries to choose the most convenient way (in his own perspective) of “managing uncertainty through time”. For this purpose, by means of the SCA, Friend proposes a method for handling any sort of uncertainties eventually emerging from a general decision process.

In particular, the author individuates three categories of uncertainties. One is associated to the environment (UE) and requires research and technical investigation. Another category of uncertainties, which is related to guiding values (UV), needs more policy guidance from an authority. Finally, the uncertainty concerning the Related Agendas (UR), demands for an exploration of the connections between the actual decision and the other to which it is related.

In Montagna (2011), the relations between complexity and uncertainty are deeply investigated. In particular, the elements considered to cause uncertainty in the NPD process seem to be related to the economic and technical operative conditions of the firm, the innovation rate required and the organizational context of the development process.

Renzi et al 2017 provide a review on engineering design methods in the automotive industry.

In order to structure the complexity elements of the uncertain and unstructured nature of some of the phases of the design process and reduce the uncertainties in decisional situations, problem structuring methods have been applied by several authors. In particular, Belton and Stewart (2002) define the problem structuring process as the one of “making sense of an issue” and identify the problem structuring as an integrated part of the process of MCDA.

2.4. KEYWORDS FOR THE REVIEW PROCESS

In order to provide an efficient review process, effective keywords have been assessed, belonging to two areas of research, namely the engineering design problems and the decision making methods. The keywords related to the former set result from the designer’s needs, which have been identified and depicted in Figure 4. The keywords related to the latter set have been extracted from the taxonomy of decision making methods which have been depicted in Figure 5.

In order to find as many matches as possible between the keywords of the two sets, all the possible combinations of the two sets of keywords have been considered. The two lists of keywords are reported in Table 2 and Table 3.

Table 2 Keywords related to design problems

Design problems
Uncertain information
New product introduction
Deep problem analysis
Problem roots
Product requirements
Customers’ needs
Preference aggregation
Alternatives selection
Compromise solution
Performance evaluation
Material selection
Manufacturing process selection
Industrial equipment selection

Table 3 Keywords related to Decision Based Methods

Decision Based Design methods
Analytic Network Process (ANP)
FUZZY- Analytic Network Process F-ANP
Analytic Hierarchy Process (AHP)
FUZZY- Analytic Network Process (F-AHP)
ELECTRE
FUZZY-ELECTRE
PROMETHEE
FUZZY-PROMETHEE
TOPSIS
FUZZY TOPSIS
Quality Function Deployment (QFD)
Soft System Methodology (SSM)
Kepner-Tregoe (KT)
MAUT/MAVT
Goal Programming (GP)
Pugh’s Controlled Covergence (PuCC)

3. RECURRENT TOPICS IN DECISION-BASED DESIGN

Before presenting the results of this review process, some aspects are worth to be pointed out, to provide a more complete background in the use of DBD techniques.

Many issues dealing with the modeling of engineering design problems, emerging from the search process, have been reported here, as recognised as fundamental within the design research community. In particular, problems related to the management of uncertainties in the early design stages, the description of designers' and consumers' preferences, the pairwise comparison of design alternatives, and the integration of the consumers' preferences in the engineering design process are tackled and analysed in the following sections.

3.1. UNCERTAINTIES MANAGEMENT IN-DESIGN PLANNING

Several examples of methods for handling uncertainties during the early design stages are collected in literature. In particular, in this section are reported the most used techniques in design contexts, namely: the Problem Structuring Methods, the Kepner-Tregoe method, and the Heuristic techniques.

Other techniques deal to the use of probability distribution for modelling the presence of uncertain factors in the design planning phase (e.g. Martinez-Cesena and Mutale 2011, Cheng et al 2002) or to the identification and control of uncertainty in complex design problems (e.g. Norese and Montagna 2008).

Malak et al (2009) individuate two causes of uncertainties, namely, variability and imprecision. The former is an objective uncertainty, related to the random physical nature of a process, as errors in manufacturing or in the communication systems. Variability can be stochastically represented by a probability density function. From a decision perspective, the variability can be handled by means of the probability theory and maximization of the expected utility. On the other side, imprecision is linked to the lack of knowledge, which can be mathematically represented by means of intervals.

Since an imprecise form of uncertainty characterizes conceptual design, new decision-making approaches should be introduced. In fact, existing MCDM methods based on the preference assessment, as the MAUT, are not suitable to be used in an imprecise context. This is mainly due to the difficulty in recognizing the concept leading to the most preferred design. For that reason, Malak et al (2009) propose a set-based design that is able to eliminate evidently inferior alternatives, without focusing on a specific one

The planning problems, to be solved in the early design stages, are often non-structured or ill-posed problems. In those cases, the Problem Structuring Methods (PSM) have proven to be effective, for assisting the designer in taking strategic and difficult decisions other than in uncertain situations and unstructured problems. Accordingly, methods for facilitating communication between customers and designers - or among the members of an organization- and mapping the reasoning by proposing different scenarios for the future, could be useful tools to point out misleading information or hidden needs. For example, the Strategic Choice approach (SCA), which belongs to the set of PSM helps focusing on decisions and strategically managing related uncertainties. In order to facilitate the process, a software (Strategic Adviser, or STRAD) - developed since the end of the Eighties and following the SCA approach - is used for complex and uncertain planning situations (Cartwright 1992). STRAD is based on the assumption that decision-making is a balance of four complementary aspects (shaping, designing, comparing and choosing). Furthermore, the software is considered a useful support for facilitating communication among the members of groups, during the decisional process, for dealing with uncertainties in messy and unstructured problems or to record the progresses made by the group, during a brainstorming session.

In literature, several examples regarding the use of the SCA are dedicated to plan decisions in other areas as urban planning, organizations, public policy, and rural development (Cartwright 1992, Kammeier 1998).

Notwithstanding this, very few of them are explicitly dedicated to the planning process of an industrial product. Among the most significant examples, one is by Friend (1989) and regards the strategy chosen for deciding about the future of an organizational project group. SCA is used for finding the most effective launching strategy for an innovative decision making software. The procedure that consists of analysing the problem under the four stages, (shape, design, comparing and uncertainty) seems to be a useful application for guiding the decisions related to the organizational areas. For these reasons, the case study proposed seems to be streamlined for managing uncertainty during the planning phase of a new product.

Another application of SCA is the work of Amata et al (2005), in which decisions taken for planning a space mission analysis are tackled with the help of SCA. This technique reveals to be effective in shaping and designing the problem and in building possible alternatives to a problem, apparently lacking of possible solutions and criteria.

For what concern SSM applications, Presley et al (2000) identify a method for collecting information and structure requirements during the planning phase. The authors present an organizational methodology for process and product innovation, which is based on a SSM model and incorporates QFD and IDEF0 techniques. The QFD is used in order to elicit information and gather the customers' requirements, while the latter technique is well adapted to the SSM methodology, as -likewise to SSM- it is able to both put the problem in a hierarchical order and decompose it.

In addition, SSM is used for the new product introduction (NPI) problem, (Page and Thorsteinsson 2007) in which it is applied in the definition and solution of the problem, in order to reduce or exclude delays.

Boardman and Cole (1996), propose a SSM for describing the problem of improving the capital goods manufacturing process. Boardman and Boardman (1997) apply the SSM to improve the Product Introduction Process (PIP) within an integrated aerospace manufacture. In particular, the research is focused on product processes and relative improvements, instead of on product manufacturing technologies. The tool kit developed (Boardman Soft Systems Method (BSSM)) has been used in collaboration with aerospace industries, for process simulation and optimization of a jet-engine.

The Kepner-Tregoe (KT) method is nowadays used in complex design contexts, characterized by a high level of uncertainty and lack of data, that is typical of the early design stages. The KT method is a decision-aiding support system, involving four steps for analyses purposes, namely: the Decision Analysis, the Problem Analysis, the Potential Problem Analysis, and the Strategic Planning.

Kepner and Tregoe (1965) remark that usually managers are required to solve problems that require an accurate analysis, to find relative problem causes. Correct the cause of a problem means finding the most effective action to solve the problem and minimize the costs and disadvantages.

In the "Strategic Planning" step, a five-phases- strategy model is individuated, for enhancing decision planning, in complex problems. In particular, the procedure starts gathering data concerning markets, competitors, technology and the internal/external environment, in which the organization would be required to operate. Therefore, some crucial strategic elements are defined, as the scope of product and services, the market and the business goal. At this step, the planning is to be implemented, by means of a project management tool, in order to achieve a detailed definition and a scheduling of each project. Several methods have been used for the preliminary design of complex industrial components (e.g. Francia et al. 2008, Renzi 2016, Renzi and Leali 2016, Renzi et al. 2014). A successive implementation of the strategy needs for iterative interventions, providing monitoring and modifications, in order to verify the validity of the previously assessed assumption.

An example of Strategic Planning is present in Curra 2006, in which an intervention of KT for process planning optimization resulted in a 15% increase in production and an enhancement of knowledge and expertise for the company.

The KT Decision Analysis method is used also for components selection problems (Hall 1980) or for hot fix intervention, after Problem Analysis. Several problems related to industrial manufacturing, automotive, aeronautics, energy, transports, and telecommunications are solved by means of the KT method. Other examples regard the enhancement of the industrial production, for fixing low production problems, the introduction of new products into the market and product quality increase.

Heuristic techniques take their basis on the way people make inferences, predictions and decisions, starting from imprecise and uncertain information. Heuristics for decision-making purposes, have been tackled by Gigerenzer and Todd (1999).The authors recall the "Franklin's moral algebra" (or Franklin's rule), in which advantages and drawbacks for each reason of a problem are assessed at first. Hence, proper weights are assigned, before proceeding with the elimination of surplus reasons, by means of addition operation, in order to accomplish balance and find the correct alternative

However, this method, based on unbounded rationality, is clearly unsuitable for real situations, due to complexity, time and knowledge constraints. Therefore, Gigerenzer and Todd (1999) propose three kinds of Heuristic methods, which are defined as "fast and frugal" (F&F) and are showed to be interesting and intuitive-based methods, for accomplishing acceptable results in real and complex problems. These procedures, namely, "Take the Best", "Take the Last" and the "Minimalist", are based on the recognition heuristic. This means that if only one of the alternatives is remembered, this one is to be considered with the higher value, with respect to the criterion. Thus, a stopping rule can be introduced in the process, as the object is recognized. In case the recognition heuristics can be applied, no need for further knowledge is necessary and the solution to the problem is, thus, found. Otherwise, other information have to be considered. Experiments have been carried out for examining the accuracy and reliability of these methods, in relation to more complex techniques, based on multiple regression calculations. They resulted to behave equally, even if complex techniques used more information than the ones required by the F&F heuristics. F&F heuristics appeared to be at least as accurate as rational- judgment- based methods. Thus, according to the accomplished results, the authors remark that simplicity has not to be sacrificed for enhancing accuracy, in decision-making methods and complex problems do not always need for complex solution techniques.

3.2. CONSUMER PREFERENCES

Traditional design processes involve the user only in the initial stages, for product requirements identification purposes (e.g. Ulrich and Eppinger 1995, Pahl and Beitz 1996). Nevertheless, the development of competitive products is based on a strong interaction between the designer and the user (Gologlu and Mizrak 2011). The involvement of both the designer and the user needs throughout the phases of the design process is a key issues in the development of successful products (Cooper 1995, Karkkainen and Elfvengren 2002). Therefore, two sources of product requirements have to be considered, namely the engineering requirements and the marketing requirements (Chen et al 2013). The former involve essentially design, manufacturing and technical fields, other than corporate, regulatory and physics. The latter directly derive from the user needs and involves multidisciplinary fields, as market research, economics, cognitive science, and social science.

For these reasons, even if marketing requirements and engineering requirements are nowadays still separated, they both have to be fully integrated throughout all the steps of the design process, in a user-centered approach (Krishnan and Ulrich 2001, Dieter and Schmidt 2008, Hoyle and Chen 2007).

The search of more rigorous design approaches, in which the views of both the user and the designer are deeply interconnected, have therefore to be achieved (Chen et al 2013).

The quest for rigorous approaches has led to the identification of DBD methods for guiding industrial designers through the design phases. This is an open issue in the design research community, so that several approaches and frameworks have been proposed and discussed for their validation (Olewinik and Lewis 2006).

Voulgari et al (2013) list the several tools regarding the integration of the user needs within the early design phases. These tools involve a multiplicity of methods deriving from several disciplines, namely, from industrial/design engineering (QFD, AD), psychophysics (Multidimensional Scaling, Pairwise Comparison), Multicriteria Decision Analysis (Expected Utility/Value Theory (EUVT), preference aggregation models, AHP, ELECTRE,…), marketing (Semantic Differential Method, Conjoint Analysis), artificial intelligence (Method of Imprecision, Kansei Engineering Methods), statistical analysis (Factor Analysis, Principal Component Analysis, Design of Experiments, Metamodels). These methods are used alone to address specific contingent design problems or can be combined to enhance their efficiency (annou and Petiot 2005).

Among them, QFD is widely used for translating the user requirements into technical requirements (Cristiano et al 2001, Miguel 2005), even if some limitations have been addressed in literature [Aungst et al 2013]. Many authors propose some enhancements of this technique. Hoyle and Chen (2007) for instance, propose the Product Attribute Function Deployment (PAFD), for generating engineering attributes, by conceiving the design process as an enterprise-driven engineering design process. Leary and Burvil (2007) propose a modified QFD that avoids the use of those requirements affecting the feasibility of the design solution.

In Wassenaar and Chen 2003 a lack of analytic techniques for modeling the customer preferences in engineering design is denounced. Hence, a Decision Based Design flowchart, basing on the work of Hazelrigg (1998) is proposed, in which the DCA is involved in the building of the product demand model.

Other methods are combined into hybrid forms, for evaluating the customer needs and integrating them within the design cycle, since the early design stages (Yannou and Petiot 2005), multidisciplinary approaches (Zhang and Anyali 2014), Fuzzy-QFD combined with ANN/GA (Abdolshah and Moradi 2013).

Several researchers addressed themselves in providing approaches to collect user preferences, in order to increase the user's satisfaction level. Most are dedicated to a design approach methodology, without providing web-based tools for industrial contexts. Only few, which derive from the field of ICT, use web-based tools for user needs and preferences elicitations.

In Gologlu and Mizrak 2011 a methodology with an integrated tool environment that helps designer is proposed to build effective customer-oriented products. The tool employs a fuzzy logic approach, to handle customer's linguistic or imprecise demands, which are generally in an intangible format, in conjunction with a CAD tool, for better visualization of the product modifications

Lin et al (2011) propose a fuzzy Product Life Data Management (PLDM), combining the Fuzzy Logic and the Conjoint Analysis. In particular, fuzzy rating is used to simulate customers' purchase decisions, including preference uncertainty. A questionnaire was posted on a web site and announced on several popular specific product websites.

In Hui and Azarm 2000, an integrated approach for product design selection, involving designer preferences, customers preferences, and market competitions is proposed. In this model, a large variety of customer preferences and market competitions are handled, together with the uncertainty related to the demand and market competition. Moreover, the evaluation of the design alternatives is extended, starting from the model proposed by Hazelrigg (1998).

Other frameworks are proposed in the literature for integrating decision making engineering design process and marketing purposes (Gupta and Samuel 2001; Michalek et al 2004]

3.3. DESIGNER PREFERENCES

Arrow (1950) who analysed it in the "Impossibility Theorem" has described the problem of aggregation of the preferences of several individuals over a set of opinions, into a common preference order. Arrow states that no mathematical application is able to solve problems concerning the collection of many individuals' preferences into a common rank (Franssen 2005). Some consequences of this theorem are visible in engineering design. In fact, an industrial project is carried out by a team of designers, coming from several different disciplines, who may diverge during the selection of the best design alternative. This issue, which can be considered as a multi-criteria selection problem, can be investigated by means of the Arrow's Impossibility Theorem (Franssen 2005, Hazelrigg 1998, Dym et al 2002).

Scott and Antonsson (2000) discuss the validity of the Arrow's Impossibility Theorem within engineering design. They remark that many multicriteria decision methods found their bases on the aggregation of preferences and on the explicit comparisons of their degrees. On the contrary, this kind of aggregation does not take place within a social choice problem. Moreover, Arrow's Theorem offers a sort of caution to compare preferences explicitly, as an improper assignment of numbers to alternatives, or the use of an unsuitable aggregation method, might lead to unreliable solutions. The authors point out that the use of a utility function, to lead decisions under uncertainty and a direct specification of preferences, might elude the problems raised by the Arrow's Theorem.

Sen (1993) argues against the imposition of the axiomatic "internal consistency" of choice, namely, conditions for which different parts of a choice function have to show specific internal correspondences. As a support of this argument, the author remarks that choices are not statements called to be necessarily consistent one to the others. Nevertheless, the internal correspondences between choices are not to be refused. The necessity of denying an a priori imposed "internal consistency" of choices is particularly evident in social choice theory, in which the interpretation of social preference and therefore imposition of axioms is difficult to be assessed. Finally, Arrow's Impossibility Theorem is re-characterized and re-established, by means of logical and mathematical formulations, by Sen (1993), showing the way to avoid the imposition of such axioms of internal consistency of choice.

A description of some drawbacks in design methods using the aggregation of preferences was reported in two letters to the Editor of the Research in Engineering Design journal. In those papers, Hazelrigg (2010) argued about several issues concerning drawbacks in design methods, present in Frey et al (2009), regarding the PuCC method. Frey et al (2010) answered accordingly to those points, rising interesting debates (Renzi et al 2013). Hazelrigg (2010) affirms that in PuCC method, the use of voting subsists. In this case, according to the Arrow's Impossibility Theorem, since any use of voting would lead to unreliable results, the entire PuCC method would be invalidated. Frey et al (2010) discussed about the meaning of the word "voting", improperly defining the action of application of symbols to fill in the matrices. Therefore, in order to provide proves to their assessment, Frey et al (2010) performed an experiment, involving a group of political scientists and sociologists, who were called to watch a video of engineers using the Pugh method. Then they were asked if they had identified stages of voting within the process. Most answered negatively. Consequently, most of experts in Pugh's method would not consider the allocation of symbols to matrices as a voting procedure. Nonetheless, the disagreement about the word voting can be simply understood. In fact, the necessity to involve a facilitator for guiding decision makers, in expressing their opinions, could be considered as an opportunity for conveying a judgment. On the contrary, actually, this should be seen as way of expressing one's own reasons, bringing new information for the members. More precisely, -as Frey et al 2010 remark- there is no action of counting votes nor comparisons to a previously chosen standard, within the Pugh's method.

Moreover, in the same editorial letter, Hazerligg (2010) deals with the role of shortcuts in engineering. The author states that apparently easy methods, as PuCC, could be chosen for their non-analytical form. However, the user should prefer mathematically proven methods, ensuring the achievement of a good result, even if their use requires fatigue and elapsed time. Frey et al 2010 reply that simplification of a task is an appreciated skill for an engineer to solve problems under time and cost constraints, without losing information. Therefore, they point their attention on the most efficient methods to be preferred to other analytical methods, although less mathematically rigorous.

Again, Hazelrigg (2010) states that Pugh's method would potentially fail in selecting alternatives, as the number of attributes and of designs increases. This however, – as Frey et al (2010) remark - could be due to the fact that as more options are considered and more design alternatives are added, the probability of choosing a good design candidate increase.

Hazelrigg (2010) makes another interesting remark, about the validity of design methods. He assesses that, if a method has been showed to be successful in few cases, while failing most of the times, this cannot be considered a valid one. This fact, as replied by Frey et al (2010), is valid in a mathematical context, in which methods exist whose validity can be tested, within the whole domain. On the contrary, design does not have methods that give exact results within the entire domain, and therefore, counterexamples cannot be considered. For example, a plausible domain in engineering design could be the generation of alternatives, for which it has no way to find the correct results, but it is only reasonable to get better results.

Barzilai (2006) remarks that there exist only one model of strong measurement for preference. As in the Principle of Reflection, all models of classical theory of measurement generate weak scales to which the above mentioned operations are not applicable. In order to avoid this drawback, the objects must be mapped into the real one dimensional homogeneous field, that is one-dimensional affine space

3.4. PECULIARITIES OF THE PAIRWISE COMPARISONS APPROACHES

The pairwise comparison approach seems dangerous, as it is capable to undesirable rank reversals. Rank reversal is an alteration of ranking of alternatives, by addition or deletion of irrelevant ones (Buede and Maxwell 1995). Belton and Gear (1983) first denounce the rank reversal problem linked to AHP. Hence, recommendations for changing to AHP - as removing the normalization of the ratio scale for the criteria - are reported in literature (e.g. Dyer 1990, Barzilai and Golany 1991).

In a series of experiments, Buede and Maxwell (1995) examined the frequency and magnitude of rank disagreements. In particular, the results of the application of MAVT were compared to three methods allowing rank reversal, (AHP, Percentaging, and TOPSIS) and to a Yager's Fuzzy algorithm (Yager 1978). The experiment revealed that AHP, despite the other techniques, best fitted M VT.

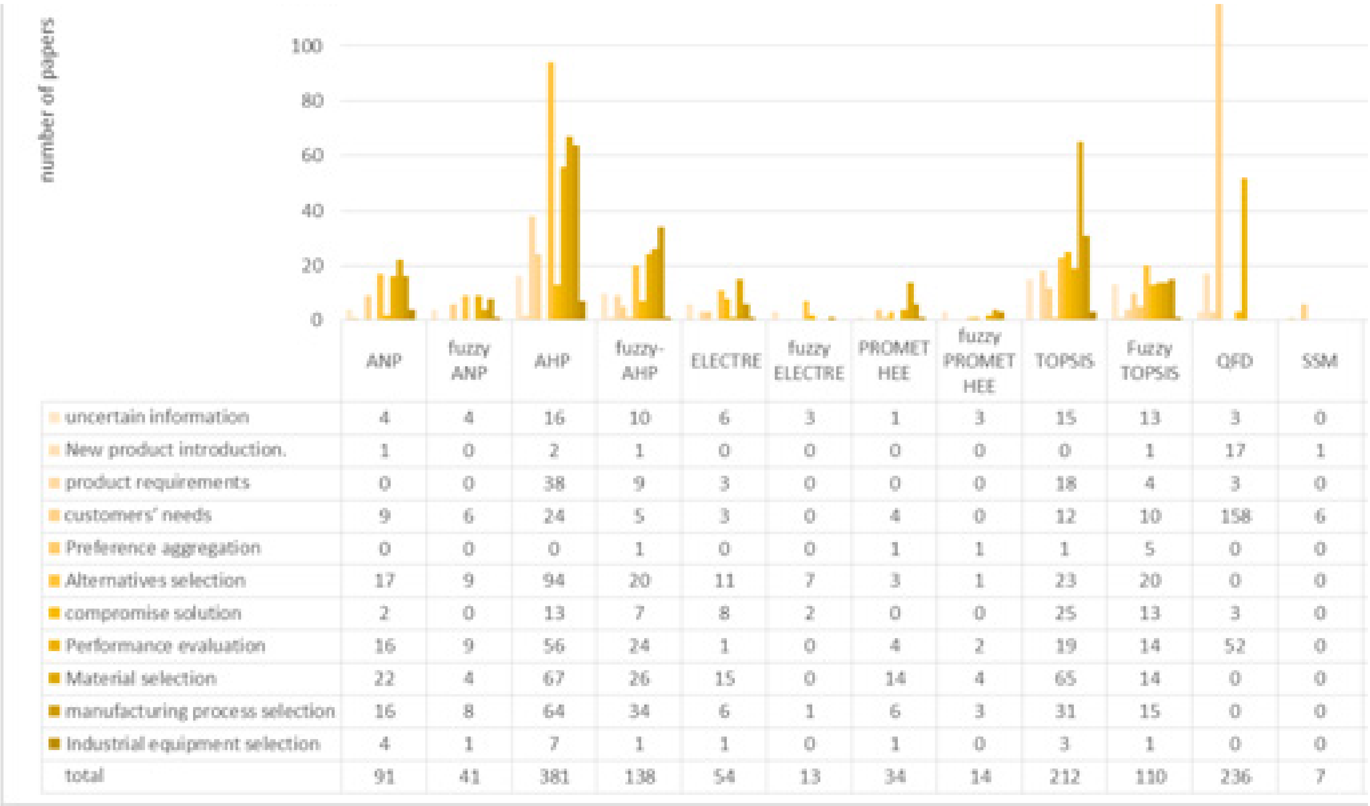
Moreover, rank reversals are linked to the problem of losing information, such that several noteworthy methods have been developed in order to overcome the problem. According to Saari and Seidberg (2004), the loss of information brought by the pairwise comparisons could be avoided with an alternative form of Borda Count. However, Dym et al (2002) show that in practical engineering design, the Pairwise Comparison Charts (PCC) provide the same results as the implemented Borda Count. The authors remark that rank reversals and other drawbacks could derive from the aggregation of pairwise comparisons, when some information about the alternatives that gain minimum voting are not an object of further analyses.

Johnson and Busemeyer (2005) illustrate a dynamic stochastic computational model (Sequential Value-Matching (SVM)) for avoiding rank reversal phenomena and introduce six elicitation methods to predict preference orderings. Starting from the assumption that preference should be seen as a dynamic and stochastic process, evolving across time, the authors expand the dynamic theory of preference (decision field theory (DFT) of Busemeyer (Busemeyer & Goldstein, 1992)). Thus they generalize their theory to the binary choices, under risk conditions and include the indifference response into the same choice model. Finally, they present a matching model, hierarchically driven by the choice representation, for measuring preference values. Before them, Diederich 1997 perceives the double nature -dynamic and stochastic-of the decision making process and, thus, includes it into a Multi-Attribute Dynamic Decision Model (MADD). The model proposed is based sequential comparisons, generalizing the decision field theory (DFT) of Busemeyer. In particular, the author focuses on decision making under time constraints, describing the model's predictions in this context. Katsikopoulos and Martignon (2006) studied three heuristics for paired comparisons, based on binary cues, following different approaches, the linear one and the lexicographic. They present results on the accuracy of the methods, according to the dependency on cues and their number. Limayem and Yannou (2007) show several indicators, provided in literature, for inconsistencies in pairwise comparisons, during group decisions. Thus, they identify a selective indicator for inconsistencies, which corrects the ones individuated by the group, according to the selected voting strategy.

4. DISCUSSION

As specified in the section related to the description of the review method, in Figure 4, the designers needs have been individuated, for the identification of the engineering design problems. Accordingly, related keywords have been listed (as reported in Table 2) and used for the search process. Similarly, starting from the taxonomy analysed and reported in Figure 5, the keywords related to the DBD methods have been identified (Table 3).

All the possible matches resulting between these sets as well as the quantitative results of this review process have been analysed. As a result, in Figure 6 is reported the occurrence of use of decision-based methods, in relation to the engineering design problems to be solved.



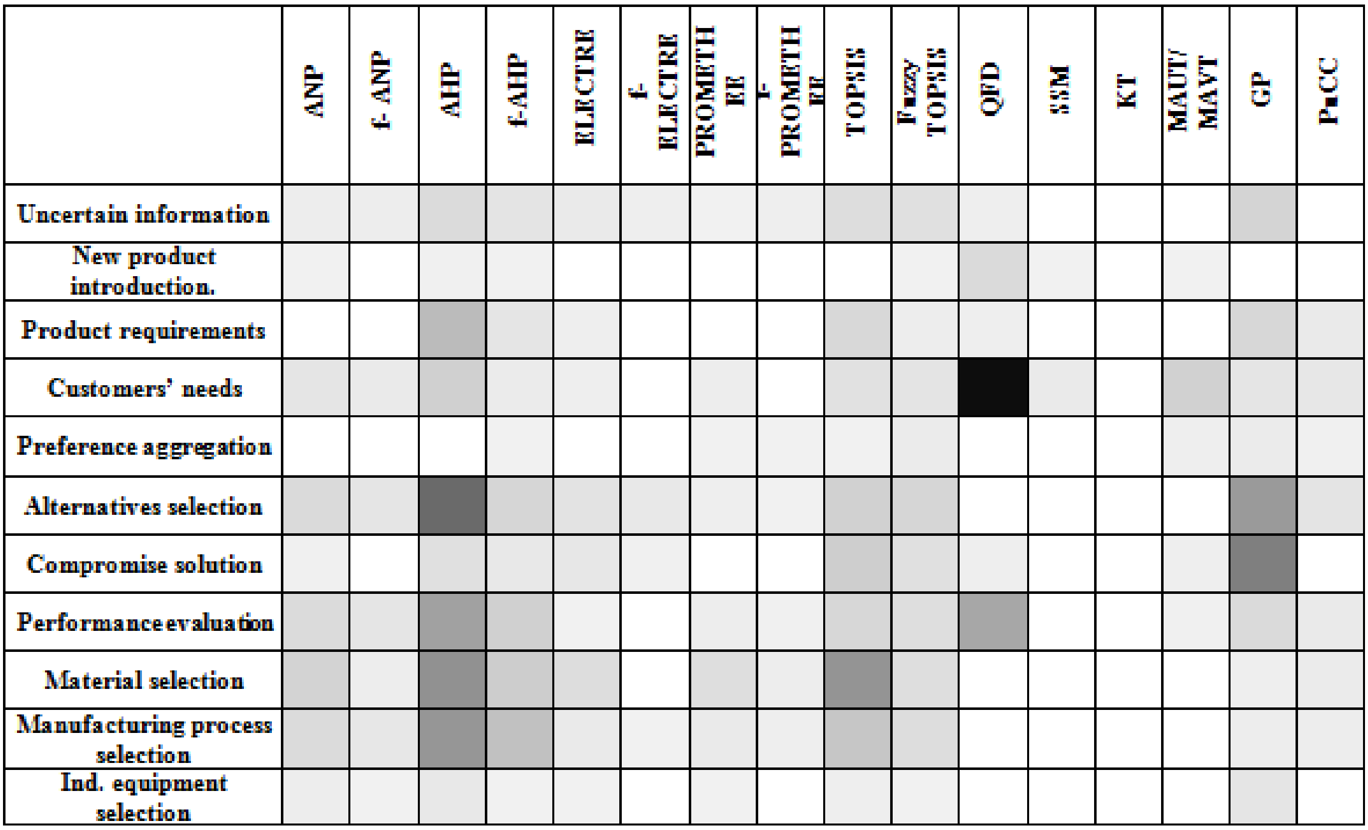
	ANP	fuzzy ANP	AHP	fuzzy-AHP	ELECTRE	fuzzy ELECTRE	PROMETHEE	fuzzy PROMETHEE	TOPSIS	Fuzzy TOPSIS	QFD	SSM
■ uncertain information	4	4	16	10	6	3	1	3	15	13	3	0
■ New product introduction.	1	0	2	1	0	0	0	0	0	1	17	1
■ product requirements	0	0	38	9	3	0	0	0	18	4	3	0
■ customers' needs	9	6	24	5	3	0	4	0	12	10	158	6
■ Preference aggregation	0	0	0	1	0	0	1	1	1	5	0	0
■ Alternatives selection	17	9	94	20	11	7	3	1	23	20	0	0
■ compromise solution	2	0	13	7	8	2	0	0	25	13	3	0
■ Performance evaluation	16	9	56	24	1	0	4	2	19	14	52	0
■ Material selection	22	4	67	26	15	0	14	4	65	14	0	0
■ manufacturing process selection	16	8	64	34	6	1	6	3	31	15	0	0
■ Industrial equipment selection	4	1	7	1	1	0	1	0	3	1	0	0
total	91	41	381	138	54	13	34	14	212	110	236	7

FIGURE 6 FREQUENCY OF USE OF DECISION-BASED METHODS IN RELATION TO THE ENGINEERING DESIGN PROBLEMS.

In Table 4, the use of decision based design techniques in the engineering design problems is depicted by means of a coloured map. The lower the colour, the higher the frequency of usage of the specific method. A similar approach is used in Figure 7, for depicting the distribution of papers treating DBD methods for solving a specific design problem

A representation of the percentage of usage of decision-based techniques for each design problem is proposed in Figure 8.

TABLE 4 MAP OF THE FREQUENCY OF USE OF METHODS FOR EACH DESIGN PROBLEM



	ANP	f- ANP	AHP	f-AHP	ELECTRE	f-ELECTRE	PROMETHEE	f-PROMETHEE	TOPSIS	Fuzzy TOPSIS	QFD	SSM	KT	MAUT/ MAVT	GP	PaCC
Uncertain information	░	░	░	░	░	░	░	░	░	░	░				░	
New product introduction.	░		░	░						░	░	░		░		
Product requirements			▒	░	░				░	░	░				░	░
Customers' needs	░	░	░	░	░		░		░	░	█	░		░	░	░
Preference aggregation				░			░	░	░	░				░	░	░
Alternatives selection	░	░	▓	░	░	░	░	░	░	░					▒	░
Compromise solution	░		░	░	░	░			░	░	░			░	▓	
Performance evaluation	░	░	▒	░	░		░	░	░	░	▒			░	░	░
Material selection	░	░	▒	░	░		░	░	▒	░					░	░
Manufacturing process selection	░	░	▒	░	░	░	░	░	░	░					░	░
Ind. equipment selection	░	░	░	░	░		░		░	░					░	

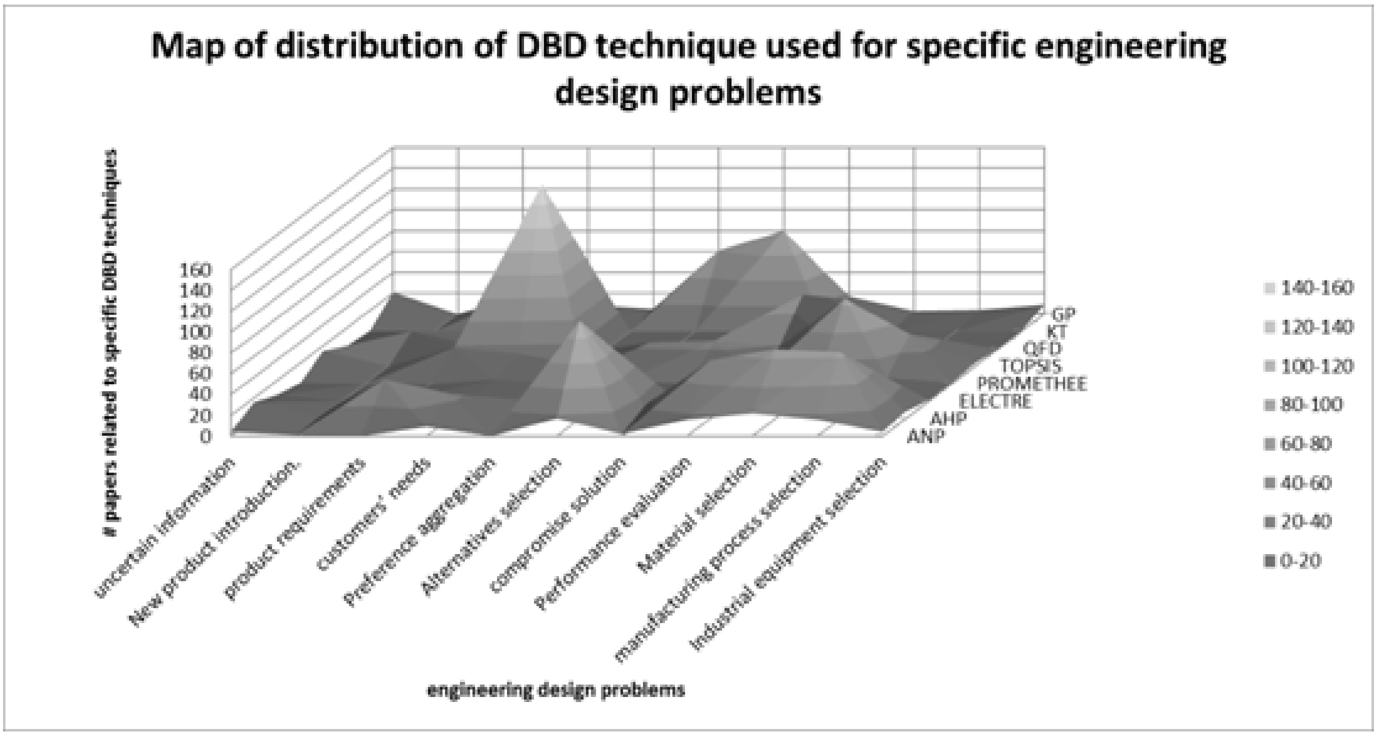


FIGURE 7 MAP OF DISTRIBUTION OF DBD TECHNIQUE USED FOR SPECIFIC ENGINEERING DESIGN PROBLEMS

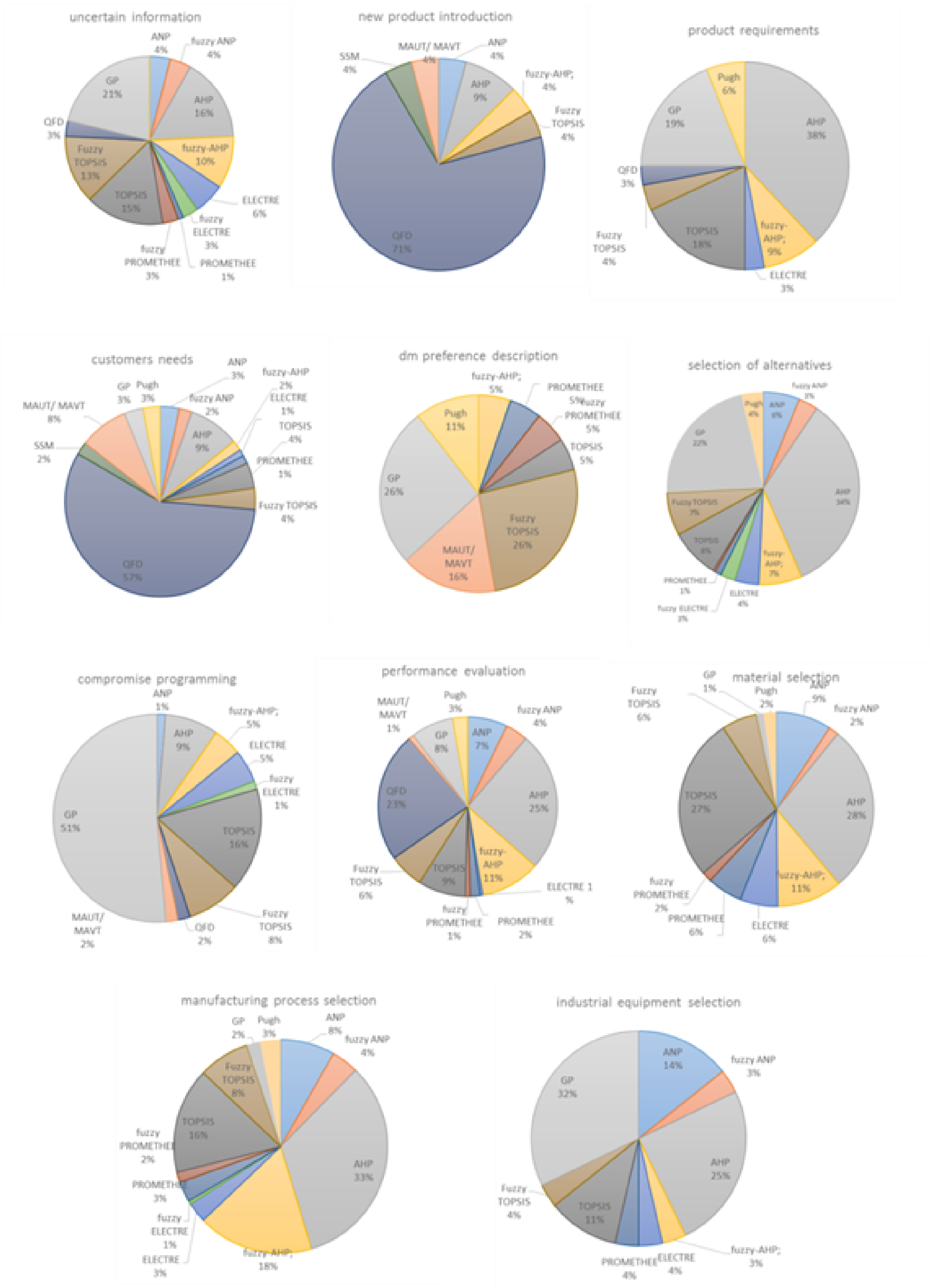


FIGURE 8 PERCENTAGE OF USE OF DECISION-BASED TECHNIQUES, FOR PROBLEMS RELATED TO THE REPRESENTATION OF CUSTOMER'S NEEDS INTO THE PRODUCT DESIGN.

A first look at the results gathered in Figure 6, Figure 7 and Figure 8, allows to deduce that the most used technique for solving multicriteria decision problems, related to product design, is the AHP method. As aforementioned, this technique is flexible and useful for cases studies of different disciplines. Other commonly used techniques are QFD, TOPSIS and Goal Programming. QFD is used for translating the customers' needs into product specifications, TOPSIS is applied for solving selection problems, Goal Programming is used for searching an efficient compromise solution

In particular, in the early design stages, the management of uncertain information seem to be tackled by goal programming techniques. The introduction of new products are carried out by means of the QFD. The product requirements are mainly defined by means of the AHP technique and Goal Programming. Other than with the QFD, the customers' needs are identified by means of the AHP and the Value measurement methods.

The problem of preference aggregation seems to be mostly handled by means of the Fuzzy-TOPSIS and the Goal Programming.

The problem of the selection of alternatives, other than the AHP, is mostly tackled by means of the Goal programming and the TOPSIS/Fuzzy-TOPSIS methods. The evaluation of the performances of a product are largely handled by means of the AHP, fuzzy-AHP and the QFD.

The selection of the most suitable manufacturing processes as well as the selection of industrial equipment are mostly tackled by means of the AHP, TOPSIS, Fuzzy TOPSIS and Goal Programming.

PuCC technique is commonly addressed for the selection of design alternatives, the definition of product requirements, the description of the customer's needs and the evaluation of the product performance.

Another result that is worth to be mentioned is the lack of papers related to the Kepner-Tregoe methods as well as a small number of applications of Problem Structuring Methods within the scientific literature. This result should encourage researchers in applying them to industrial applications.

As depicted in Figure 6, Figure 7 and Figure 8, and highlighted in Table 5, some techniques, which are traditionally associated to the solution of specific MCDM problems, seem to be used also in other design contexts.

Table 5 Expected VS found techniques for MCDM in design problems

	Expected use	Resulted use
Uncertain information	PSM	GP/AHP/TOPSIS+F-TOPSIS
New product introduction	QFD	QFD
Product requirements	MAUT/MAVT	AHP/GP/TOPSIS
Customers 'needs	QFD	QFD/AHP+F-AHP/MAUT/MAVT
Decision maker's preference description	MAUT/MAVT	Fuzzy-TOPSIS/GP /MAUT/MAVT
Alternatives selection	AHP/ELECTRE/PuCC	AHP/GP/TOPSIS/ELECTRE
Compromise solution	GP	GP/TOPSIS+F-TOPSIS/ELECTRE
Performance evaluation	GP/TOPSIS	AHP/F-AHP /QFD/TOPSIS+F-TOPSIS
Material selection	selection methods indiscriminately	AHP+F-AHP / TOPSIS/ANP
Manufacturing process selection	selection methods indiscriminately	AHP+F-AHP / TOPSIS/ ANP+F-ANP
Industrial equipment selection	selection methods indiscriminately	GP/AHP+F-AHP/ANP+F-ANP/TOPSIS+F-TOPSIS

As an example, unlike what might be expected, the problem of managing uncertain information in early design is more frequently handled by means of the GP, the AHP and the TOPSIS (or F-TOPSIS) rather than the PSM.

On the other hand, as expected, problems related to the new product introduction are mainly tackled by means of the QFD (other than the 70 percent of usage is documented). Product requirements are mostly identified by means of the AHP technique, less by the Goal Programming technique and the TOPSIS method. The customers' needs are managed by means of the QFD technique (more than 50 percent), as expected, together with additional use of Value and Utility Theory-based techniques.

As regards the description of the decision makers' preferences, the GP technique is as frequently used as the Fuzzy-TOPSIS. Utility and Value Theory based techniques and the PuCC are used in a minor percentage.

Commonly used techniques for the selection of design alternatives are expected to be the AHP technique and other than the TOPSIS and Fuzzy TOPSIS methods. Nevertheless, the analysis results in a Goal Programming is common for the selection of design alternatives.

The compromise programming is mostly performed by means of the Goal Programming method, even if a minor percentage of the use of TOPSIS technique is present. The design performance is mostly evaluated by means of the AHP technique and the QFD technique.

The selection of materials, industrial equipment and manufacturing processes are mostly tackled by means of selection techniques. In particular, for the material selection problems and the selection of the suitable manufacturing process, literature documents the use of AHP or F-AHP , TOPSIS other than ANP or F-ANP techniques. Instead, for the selection of the industrial equipment, other than the above-mentioned techniques, a widespread use of Goal Programming is documented in the literature.

5. CONCLUSION

This review is aimed at suggesting some courses of action to the designer who is required to solve specific engineering design problems. First, the needs of the designer are pointed out within each design phase. This is aimed at finding matches between the designer's needs and decision based methods, in a designer's oriented perspective.

Hence, considering the designer's needs as the origin of the decision process means to shape a product fulfilling the industrial and economical needs, the environmental needs, the company's needs and the customers' needs. The designer is required to translate these needs in product specifications, and then solve the related design problems throughout a decision-making approach.

The results of this review process are intended to find out as many correlations between existing decision-based methods and specific design problems as possible. Interesting results highlight that several design problems, which were expected to be solved by specific design techniques, are solved also with other ones. This relevant result is capable of an enlargement of the state of the art related to the use of DBD techniques within engineering design contexts.

Further related research, which is currently being performed, is aimed at gathering industrial applications of DBD techniques, as well as specific cases studies, in order to understand the advantages and drawbacks of the use of each technique for solving a specific engineering design problem. This is aimed at providing a more complete guide for the designer, who is required to select a specific DBD technique for solving multiple criteria engineering design problems.

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