Integrated use of mathematical programming and multiple criteria methods in engineering design processes

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Maria Franca Norese (mariafranca.norese@polito.it), Ersilia Liguigli (ersilia.liguigli@polito.it)
Chiara Novello (chiara.novello@polito.it)

Department of Management and production engineering – Politecnico di Torino
Corso Duca degli Abruzzi, 24 – 10129 Torino, Italy

Abstract

A decision aiding methodology was required by a company of the aeronautical sector to support their engineering design processes. An integrated use of mathematical programming and multiple criteria methods was proposed to orient the conceptual design of functional and physical solutions.
As a first step, linear programming was used in relation to some case studies to generate design alternatives that satisfy the initial requirements. Subsequently multiple criteria methods were proposed to interact transparently with the client in relation to some aspects that were not included in the linear programming model. Design alternatives were evaluated and compared, in order to identify and formalize expectations that the first design solutions were not able to meet .
An iterative use of the two approaches, in a cyclic procedure of mutual learning, can allow the requirements to be defined more clearly and a final satisfying solution to be reached.

Key words: multiple criteria methods, requirement identification and engineering, integration of OR methods

1 Introduction

Engineering design is an iterative decision-making process which is developed to devise a component, product, process or system that meets the customer's needs (Eggert, 2005). A collaboration with the Marketing and Business Development Department (MBDD) of a company that designs and produces aircrafts for civil and military use, has allowed us to understand their main conceptual design activities (Norese et al., 2008a; Norese et al., 2012) and to propose an integrated use of mathematical programming and multiple criteria methods in order to aid engineering designers.

An aircraft is a complex system, but it can also be seen as a component of an even more complex structure, a System of Systems (SoS), in which different systems communicate and work together to achieve specific targets. In a SoS, integration and synergic work may vary from a simple collaboration, in which the single components work alone, to a situation in which the single components are not able to work in an autonomous way, if they are extrapolated from the SoS.

The MBDD supports product development by managing the relationship with the client in the initial engineering design process phase. The client's needs have to be identified in order to decide whether, and how, a specific legacy aircraft should be modified in relation to these needs, or in order to understand what kind of aircraft should be designed or (at least partially) re-designed, in order to guarantee its integration in the new SoS that the client perceives as possible or essential for the future.

The client's involvement in the initial phase of the design process is analyzed in the literature in "front end" models of the product development process (see, for instance, Smith & Reinertsen,1992; Reinertsen,1999). Some authors have focused on the concept phase of the process where, through the involvement of the client, it is possible to obtain meaningful improvements (Clark & Fuijmoto, 1991) and to resolve ambiguity and uncertainties in the customer's requirements that may cause difficulties (Smith & Reinertsen,1998).

In the aeronautical sector, a partial and limited re-design requires years of work (five years on average in this company) in a context where uncertainty regarding the evolving nature of the client's requirements is normally present, with the resulting evident impact on the engineering design process. The MBDD asked our research group for suggestions and methods in order to improve the interaction with the client (who can understand every step of the design process and freely propose his point of view), to reduce time and guarantee the quality of the results (which can be a shared solution but also a better definition of the needs, objectives, priorities and future scenarios of aircraft use).

In order to address this problem, we proposed the integrated use of two types of Operation Research methods, to be applied iteratively on some case studies, where the output of one method was the input of the other method (Belton & Stewart, 2002): Linear programming (LP) can be used to analytically define the constraints and aspirations of a client, in order to generate the widest set of design alternatives that satisfy the initial requirements (admissible solutions) and to calculate optimal solutions, in relation to specific objectives. Multiple Criteria Decision Aid (MCDA) models can be developed and applied iteratively, in order to transparently interact with the client in relation to the admissible or optimal solutions provided by the LP application. These solutions can be analysed and evaluated, in relation to aspects that were not included in the LP model, such as the perception of a risk (of using a too innovative technology, or generating new complexity in the future maintenance problems, and so on).

Specific client's requirements can be identified and formalized when a solution, which has been proposed as admissible by the LP application, results not so compatible with some expectations of the client.. At this point, new or different needs and expectations (not sufficiently clear prior to the MCDA analysis and therefore not included in the LP model) may be included in a new version of the LP model, as new functional or organization limits. A new solution development cycle can thus start, and the feasibility of solutions obtained by the previous LP model can be tested in relation to the updated model. This learning cycle continues until the requirement engineering process is concluded and an acceptable solution is finally reached.

The second section of the paper focuses on the iterative nature of the engineering design process and offers a synthetic overview of the theories and main approaches that are used in the process.

In the third section, the problem, as perceived by the MBDD, is presented and, in the fourth section, a set covering model is proposed for the generation of design alternatives.

In the last section, some multiple criteria approaches are described in relation to the evaluation of design alternatives, and the integrated use of two methods is proposed to support communication with the clients, in order to better define their needs and expectations. The future developments of our proposed approach , in relation to more complex projects and decision contexts, are analysed in the conclusions.

2 Engineering design process

Several theories and various tools are proposed in engineering design to aid designers in different ways: to understand stakeholders' needs, improve quality, address variability and uncertainty issues in the design process, or generate alternatives for designers.

The engineering design process, as described by Eggert (2005), is structured in five steps: definition of the problem, gathering pertinent information, generating multiple solutions, analyzing and selecting a solution and, finally, testing and implementing the solution. A procedure of identifying and formally listing the customer's requirements is usually present in the problem definition step where the functions and features of a new product are defined.

These activities are normally included in the first step of the design process, but in some cases problem definition is complicated and can be completed only at the end of the second step, when pertinent information is gathered. Generating and analyzing multiple possible solutions, with the involvement of the client and some areas of the enterprise (third and fourth steps of the Eggert model), could be a way to obtain pertinent information on the product design and functional specifications.

Once the structural components of the design have been identified with inputs from testing, manufacturing and marketing teams, the design team generates alternatives (conceptual solutions) that are oriented in different ways to achieve predefined goals (i.e. requirements that have to be satisfied). Based on costs, quality and risk, the most promising alternatives are subsequently selected for further analysis (Dean & Unal, 1992) in order to arrive to a final design specification that best fits the requirements. At this stage, a prototype can be built and functional tests performed to verify and, if necessary, to modify the design.

The engineering design process is not linear and its concept phase (Clark & Fuijmoto, 1991) can involve many different steps in order to clearly define the problem, prior to moving on to the operational phase where the solution is tested and implemented . During the concept phase, it may be necessary to go back to a previous step because the chosen solution may prove to be unfeasible for different reasons and may require specification redefinition, new solution generation, the collection of more information or, in the worst situation, the redefinition of the problem. This design process is a continuous and iterative process.

Several tools are commonly used to aid designers. Methodologies that have been proposed in the literature usually offer an analytically rigorous support for engineering designers. *Concurrent engineering* may be the most practical methodology to improve the design process. The approaches that are most frequently suggested to obtain input from stakeholders in the design process are the Pugh Method (Pugh, 1990), Quality Function Deployment (Akao, 1997) and the Analytical Hierarchy Process (Saaty 1980; 1994), which always incorporate subjective judgments. Others are used to generate alternatives for designers, such as TRIZ (Altshuller, 1988) and the C-K Theory (Hatchuel & Weil, 2009).

3 Problem Statement

Requirements identification and engineering are critical activities in a design process when a client is dealing with an evolving situation and cannot clearly communicate needs that are not well defined. This issue is often present in aeronautics, where many years are required to create a new aircraft, or even to update some elements of a legacy system.

A clear understanding of the client's points of view, and the functional and above all organizational constraints, is essential to identify and structure the requirements that will steer the design process. The MBDD usually arrives at a complete problem definition through a joint procedure with his client, in which a comparative analysis of promising draft solutions is conducted. These solutions are first elaborated in the MBDD, based on general technical requirements, and then the strengths and weaknesses of the solutions are discussed with the client. This approach is used to acquire essential, but latent or fragmented, knowledge elements.

The future use of the aircraft has to be analyzed, even when the innovation is related to a single aircraft component. Various types of aircraft, as well as satellites and maritime or ground systems, can be involved in order to conduct a given mission (that could be military, civil or a combination of the two situations). Innovation is often required in order to facilitate coordinated work and communication.

As discussed previously, the MBDD procedure includes two stages: in the first one, some "functionally acceptable" solutions are identified or elaborated in relation to the main functionalities that are required. In the second stage, the client's attention is focused on these solutions in order to evaluate the associated costs (which are not only monetary), their economic sustainability and specific benefits and risks, as proposed in the Office of Aerospace Studies (2002). This analysis orients the elaboration of a better solution for the client, but at the same time defines the overall problem requirements and identifies pertinent information and/or information sources. A representation of how this cyclic procedure evolves is presented in Figure 1, with indications of the main activities that are included.

In the last few years, some clients have required the use of a specific Operations Research tool, the Analytic Hierarchy Process (Saaty, 1980; 1994), in order to facilitate the comparisons of the solutions. Having found the tool very interesting, the MBDD asked our research group to develop a methodology to help the generation of all the "interesting" solutions in order to reduce time and guarantee the completeness of the solution set. We analyzed their use of the tool and the weak and strong points of their applications. We subsequently proposed an integrated use of LP and MCDA in a procedure that fits the MBDD approach to the client's needs identification and to requirements engineering. We thereby helped improve the interaction with the client, who can expose his point of view, in terms of limits of the solutions or opportunities that have to be emphasized, in a simple but formal language, and can almost immediately analyze all the new solutions and verify if they are consistent with his *constructed* new vision (see Tsoukiàs, 2008).

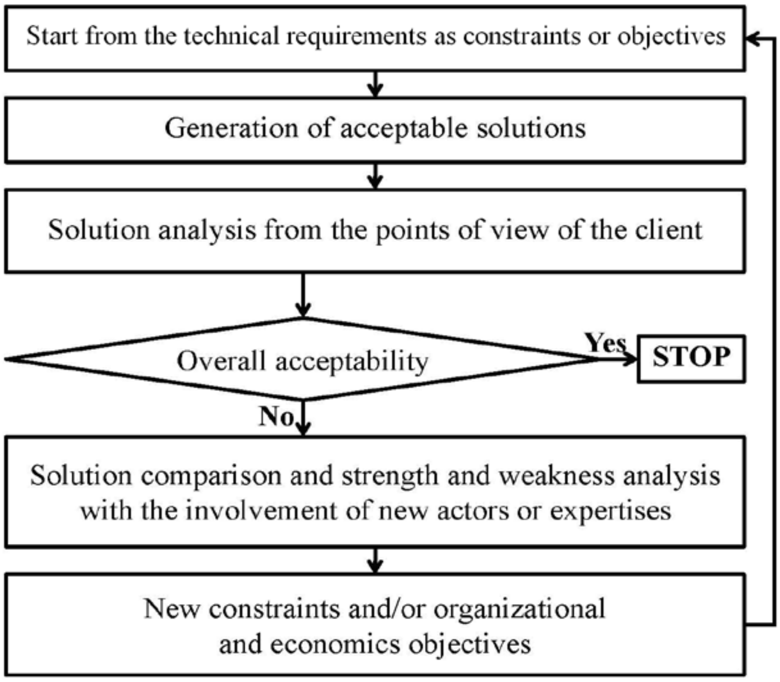

Figure 1: Proposal of a cyclic procedure in the MBDD

4 Mathematical programming application

The requests of a client can be initially formulated at a very generic level since his real needs are not always easy to understand. In some cases needs are not so clear even to him.

In order to reduce uncertainty related to the needs, the MBDD was used to express a client's request in terms of mission types that the new system (or asset) has to conduct, as a component of a System of Systems (SoS). If, for example, the context is the sea surveillance in a specific geographic scenario, the mission types that can be conducted are immigration control, smuggling, environmental pollution, mine identification, chemical/biological/radiological threat detection, and so on. The SoS can include, as main components, patrol vessels, helicopters, patrol aircraft, unmanned aerial or maritime vehicles and satellites, and all the required supports, such as surveillance radars, underwater sensors, control stations or communication systems.

From a technical point of view, an asset is a system that guarantees specific functionalities. The assets may be component parts of a single aircraft that have to be integrated to complete a mission, or to be integrated with other assets in other kinds of aircraft or in systems that operate on the ground. The assets may also be specific kinds of aircraft (or other resources) that have to be activated jointly in a specific mission. In all these situations, the integrated assets can be seen as an SoS and the adequate performances of both the assets and the relationships between them are necessary to perform the missions.

Our proposal was the definition of a mathematical model in which the variables are the different assets that can be activated to accomplish a mission. The functionalities that must be guaranteed (or guaranteed at a required level), in relation to the "nature" of the mission, can become the constraints of the model.

The objectives, in relation to a specific decisional problem, can be different: minimize the costs, maximize the effectiveness, minimize the risks of a mission and so on. A combination of assets is considered acceptable if it guarantees the Required Level of Performance (RLP) for each functionality (i.e. for each constraint of the model) and thus becomes an admissible solution, called an architecture of the SoS. The optimal solution is an admissible solution that optimizes the objective value. If no admissible solutions exist, then there are structural gaps or deficiencies in the available assets and the need for a technological innovation (i.e. at least a partially new asset) is made evident. A new product, or an improvement in a legacy system, satisfies the client's needs if all the missions identified by the client can be accomplished at a minimum cost.

A linear programming model may be used to represent all the asset combinations, if all the constraints and the objectives are linear functions. If there is only one objective, the Simplex method (Dantzig, 1963) may be used to obtain the optimal architecture. If there is more than one objective, a multi-objective linear programming method (Ehrgott & Wiecek, 2005) may be used.

At the start of the model setting, the assets that have to be included in the model (i.e. the variables) and a list of functionalities, i.e. the constraints of the model, are defined in relation to the (generic or specific) request of the client using the Universal Join Task List (UJTL) Report[1]. The UJTL was developed for the U.S. Armed Forces, and is used by several countries and international military organizations, such as NATO.

A complete list of about 720 possible functionalities, in terms of abilities to perform a task, is proposed in the UJTL Report, in relation to the strategic, operational and tactical levels of mission in a military context. The MBDD has structured and adapted the Report to facilitate its use with its clients. It has synthesized all the coordination, monitoring and controlling functionalities for military missions in the Mission Management macro functionality. Find-Fix-Track is the code that they use to indicate the set of functionalities that, at different levels of detail, allow the area of interest to be patrolled, in order to indentify and trace the target

The adapted framework includes only sixty main functionalities that must always be guaranteed in a military mission. In the model setting, the sixty functionalities are always present as model constraints. When a mission type requires a specific and not usual functionality, the UJTL Report is used as a check list in order to identify the other constraints. Each functionality can be accomplished by different assets and there are mono-functional assets that are oriented to a specific functionality, and others that fulfill several tasks (and often are innovative, complex and more expensive). An extract of the asset table, in relation to a military case, is shown in figure 2.

Macro Func.	Functions	RLP S_i	ASAM x_1	ASAL x_2	SEAD x_3	AAF x_4	AAS x_5	UCAV & CS x_6	ASEF x_7	LE x_8	GE x_9	ISR UAV & CS x_{10}	SIGINT UAV & x_{11}	ISR / SIGINT x_{12}	COM UAV x_{13}	COM Sat. x_{14}	C2 Platform x_{15}	AEW Platform x_{16}	Tanker platofrm x_{17}	SOF & Transp. x_{18}
FFT	Identification	3	3				5	5	5			5		5						5
FFT	Localization & Tracking	3				3	3		5											2
MM	Pre-mission activities	2	1	1	1	3	5	5	5			5	5	5	5	5	4			

The function i cannot be performed by asset j

p_{ij} The function i is performed by asset j with value p_{ij}

p_{ij} The function i has to be performed by asset j with value p_{ij}

p_{ij} Redundancy q_i of the function i

S_i Required Level of Performance

Legend

Figure 2: Extract of the Asset table

If the adopted objective is to minimize the number of assets that have to be involved in the proposed missions, the mathematical problem can be re-formulated in terms of a *set covering* problem, which consists in finding the minimum number of service centers (in our model, the assets) so that the request for each service (the guarantee of a required level of a specific functionality) is covered (Tadei & Della Croce, 2001).

We have formulated a mathematical model where the performance p_{ij} of the jth-asset with regards the ith-functionality is compared with S_i, the required level for the ith-functionality. The objective is to obtain the covering matrix $[t_{ij}]$, in which the elements t_{ij} are equal to 1, if $p_{ij} \geq S_i$, or 0 otherwise.

The *set covering* problem can be formulated in the following way:

$$\text{Min} \sum x_j \qquad j = 1,\ldots, m$$

[1] Report available on the www.dtic.mil website

$$\sum t_{ij}x_j \geq q_i \qquad i = 1,..., n \qquad x_j=\{0,1\},\ q_i \geq 1$$

where the decision variable x_j that is associated to the jth-asset has a value of 1 when the asset is included in the solution (an SoS architecture), and 0 otherwise. The required functionalities are guaranteed by the constraints but for some of them, a redundancy of operating assets is required to limit risk. The value of the redundancy q_i is the number of assets required to conduct the functionality i. This number is larger or equal to 1.

The model structure and the linear programming application to the problem were tested in relation to some previously used military cases, where the solutions and their characteristics were well known for the MBDD. We spent a great deal of time defining and modifying the constraints, in order to better take into account some specific requirements, but the immediate calculation of the solutions facilitated convergence towards a good model. The same procedure was then applied to a new case, in relation to the surveillance of a critical sea canal.

We used Xpress-MP, version 2007 (Mosel 2.0.0, IVE 1.18.01, Optimizer 18.00.01) to solve the linear models with a single mission or multi-scheduled missions that are included in the model. In a military case, for a three missions model with 18 assets-variables and 210 functionalities-constraints, we obtained three optimal solutions (with the same objective value, i.e. two required assets, and different combinations of assets) and six feasible ones in 0.15 seconds. In the sea surveillance case, for a two missions model with 10 assets-variables and 30 constraints, we obtained eight optimal solutions (with the same objective value, i.e. five assets, and different combinations of assets) and 108 feasible ones in 0.65 seconds.

The model development and the PL application were accepted by the MBDD as effective steps in a procedure that can support communication with the client. Then attention was focused on developing a tool to evaluate and compare the solutions obtained by the LP model (the optimal ones and, if useful, also some interesting feasible solutions) and to understand the reasons why some solutions might not be satisfactory to the client.

5 MCDA approaches

The U.S. Air Force Center of Expertise for Analyses of Alternatives suggested in Office of Aerospace Studies (2002) a multiple criteria approach in which all the aspects that are related to the effectiveness of an alternative have to be analyzed and then synthesized in an overall judgment, in a transparent way. The different costs (which are not necessary monetary) of each possible choice have to be identified and synthesized in a global cost. A scheme synthesized in Figure 3, is proposed to graphically show the alternative solutions in two dimensions, costs and effectiveness. As expected, the most effective solution is also the most expensive. The use of one or more acceptability thresholds is suggested to facilitate a decision that is not easy to make. The various uncertainties that are related to the evaluation of each alternative are also informative and could be graphically represented by the different ellipses.

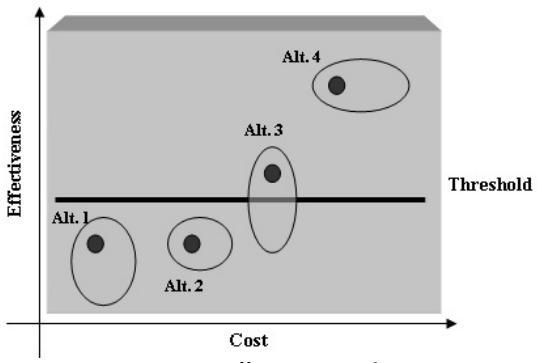

Figure 3: Cost/effectiveness analysis

The MBDD accepted and implemented this point of view and the proposal of a two-dimensional logic, but adopted a different approach when a client suggested the use of a multiple criteria method, Analytic Hierarchy Process (AHP), for the comparison of the alternatives. In their first application, the evaluation model (that was very simple, with the goal and a one-level hierarchy) included several criteria. A pilot of the client's organization, in collaboration with the MBDD, compared the alternatives thereby providing the pairwise judgments required to apply AHP.

We had the opportunity to analyse and discuss this model and how it was used in practice, which the MBDD described as not totally satisfactory, above all because the pilot's knowledge of the different points of view of his organization was limited. Further applications allowed the MBDD to realize that the correct approach has to structure the evaluation model in macro aspects that should be analysed separately with some organization-client key actors (in charge of specific aspects, such as system maintenance or management of sensor packages) as a function of their expertise. At the same time, the MBDD elaborated a way of translating each personal judgment into an analytical function.

When we analysed their latest models and the procedure they were using, we noticed that the results were very interesting, in relation to their first aim (improving communication with the client in order to understand his point of view and adequately model his requirements), but very poor in terms of documenting the decision process and the motivations behind each decision.

In fact, their analytical functions were not consistent with the logic of the method and, as we noted in some cases, only partially consistent with the original judgements. At the same time, we realized that they needed "analytical" evaluation functions in order to explicitly document the last step of the process, and not only the results. Therefore the situation was analysed together with the MBDD, to show them that their adopted procedure presented some deficiencies, and we proposed a different approach that could satisfy both their goals, without extremely changing their vision of the decision situation.

5.1 The proposal

There are many multiple criteria methods that are used to aid decision making (see for instance the classification of these methods in Figueira et al., 2005). It is necessary to choose among the various methods in relation to the specific characteristics of the decisional problem. In this case, these are essentially: transparency of the process leading to a conceptual solution; simple and adequate evaluation expressions (consistent with the analysed aspect and as "objective" as possible) and, finally, a treatment of the uncertainty that affects data and judgments.

We proposed to evaluate the applicability of two methods, AHP (Saaty, 1980; 1994) and ELECTRE III (Roy, 1978; 1990), to be integrated in a single procedure and tested in relation to the examined case studies.

Model structuring can be supported by means of AHP and its SW tool, Expert Choice, that guarantees an easily visualization of the main aspects: organizational actors and scenarios, problem dimensions and model criteria. A graphically supported sensitivity analysis is specifically suggested to facilitate the identification of model weaknesses and possible improvements or a new model structuring step. AHP does not require an "analytical" evaluation of the solutions, but comparative judgments on a linguistic scale are used both to assess the solutions on the individual criteria and to calculate weights. The procedure that synthesizes all the judgmental elements of the model is compensatory.

In the ELECTRE III method, unlike AHP, the alternatives have to be evaluated in relation to all the criteria and each evaluation has to be made explicit. Thresholds are introduced when uncertainty is present in some evaluations, to limit the negative effect of the uncertainty on the results. Criteria can have different degrees of importance and, in this case, numerical coefficients of relative importance of the criteria have to be introduced. ELECTRE III starts by comparing each solution with each of the other solutions. A fuzzy outranking relation, based on the two principles of concordance and discordance, is obtained in phase I of the method through the computation of a concordance index, a discordance index and an outranking degree. The method uses the latter result in a second "exploitation" phase, in order to construct two complete pre-orders through a descending and an ascending distillation procedure. The intersection of these two orders leads to a partial pre-order. Outranking relation modelling offers some interesting advantages, in comparison to other multiple criteria methods: each criterion can use a different ordinal or cardinal scale, since a unique transformed scale (such as the cost-benefit analysis monetary scale or the 0-1 utility scale of the multi attribute utility theory) is not necessary, and the outranking relation is not compensatory (or partially not compensatory).

A weak point of ELECTRE III is its software package[2], which does not pay any attention to dialogue with the decision maker, an essential element in model structuring and parameter definition, especially when the results must be analysed by a group collectively. A new product, which will include several multiple criteria methods and should be more suitable, is currently being developed in the Decision Deck project[3]. This weak point is related to the original nature of the method that was meant to be used when a problem was already structured, i.e. when:

- a set of solutions has been identified, or elaborated, and tested in terms of completeness, admissibility and comparability, and
- a family of evaluation functions (i.e. criteria), created to represent all the different aspects of the problem at hand, is sufficiently small to act as a basis for discussion (legibility condition) and is considered by all the actors to be a sound basis for the continuation of the decision aid study; its coherence (exhaustiveness, cohesiveness and redundancy) has been verified by operational tests (Roy & Bouyssou, 1993; Roy, 1996) that involved the decision context.

For this reason, ELECTRE III is not normally used until the problem (and/or the model) is structured and only when the previous conditions are satisfied, does it become a powerful method to transparently compare solutions, in relation to all the different criteria, and to rigorously aggregate evaluations that are associated to the consequences of each decision.

The application of ELECTRE III in relation to an unstructured problem is possible (see for instance Balestra et al., 2001; Cavallo and Norese, 2001; Norese, 2010, in this case in relation to another ELECTRE method) but its use has to be seen as a "simulated" application that is oriented to problem formulation and structuring. It requires much time and a clear attitude to criticize each result and change the model, at least marginally but often structurally. Some elements of knowledge about the problem have to be present and used as reference to interrupt the cycle when model and results become consistent with them, or as a test to demonstrate that problem and/or model do not match the problem situation.

In order to assist the MBDD in the requirements engineering of their client's needs, we proposed the following:

- the AHP should be used to structure the decision problem, when pertinent information has to be identified together with the client, by means analysis and selection of conceptual design solutions that arrive from the mathematical programming application;

[2] www.lamsade.dauphine.fr/spip.php?rubrique64
[3] www.decision-deck.org

- each new input that the client has proposed (new or changed requirements) can be integrated in the LP model;
- feasibility (or optimality) of the previous solutions has to be tested by the mathematical programming and new solutions can arise;
- the AHP should be re-used in relation to the new solutions and the learning cycle stops when the requirements are considered clear and complete.

The ELECTRE III should be used at the end of the process, when a decision has to activate the subsequent design process phases.
The structure of the AHP decision tree easily supports the approach of the MBDD to the client's decision context. Each strategic aspect, as a main branch of the tree, can be analysed with the responsible of the specific function/process or the specialists of the sectors. ELECTRE III becomes useful when the conceptual phase of the design process is finished and the alternatives are reduced to a small set of possible choices that, from a technical point of view, are not only feasible but also more effective than the excluded ones. At that moment, a specific model for ELECTRE III could focus the attention on all the (not only monetary) costs.

5.2 The application of an integrated procedure

In order to support interaction with the client, different models were elaborated in relation to case studies, in the military context of the fight against terrorism and in the sea surveillance context to control immigration and smuggling. The models were used, during some simulation sessions in the MBDD, to compare architectures of the SoS that were previously elaborated with the support of a LP model.

In the cases that we analyzed, the aircrafts and the other systems were already under production, or at least in the final phases of the production process, and the nature of the missions was clear to the MBDD. Therefore, the main aspects of the evaluation problem were easily identified and their disaggregation into organizational, functional and economic components was visualized through the SW Expert Choice and its multilevel decision tree.

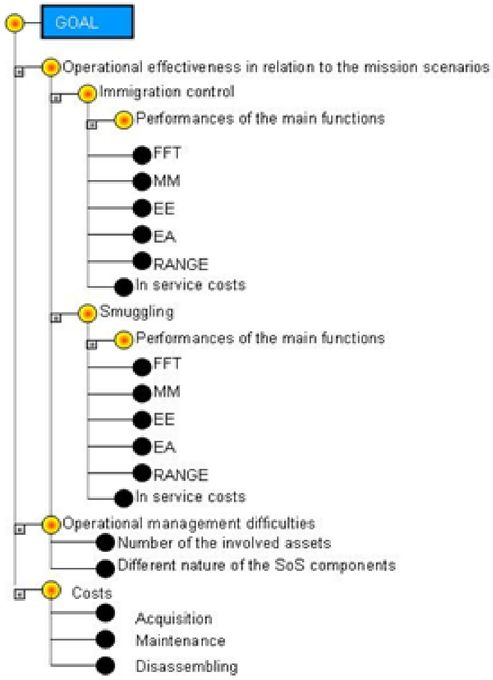

Figure 4: The decision tree in relation to the sea surveillance case

The models and the results of some applications were analyzed to understand their potential to facilitate communication between the MBDD and their different clients. We arrived at the elaboration of an AHP-Expert Choice model that is sufficiently general to be used as a first framework in different decision situations. The decision tree presents five levels. Seventeen elementary components (for a single scenario of mission, plus eight components for each other mission scenario) are proposed in the decision tree for the comparison of the solutions. In figure 4 the general model is applied in relation to the case of sea surveillance. The goal is "setting of the requirements and selection of the best SoS architectures by a comparative analysis". The main branches are "operational effectiveness in relation to the mission scenarios" (in terms of Performances of the main functions and In service costs), "Operational management difficulties" (that are related to the Number of the involved assets and the Different nature of the SoS components) and "costs" (of Acquisition, Maintenance and Disassembling).

A partially new model for ELECTRE III has to be elaborated in relation to each specific case study and to the nature of the alternatives that had been selected following the integrated application of the mathematical programming and the

AHP. A specific attention has to be focused on the different scales used to evaluate the SoS architectures, in order to easily and clearly document the evaluation process. Uncertainty is often associated with the evaluations (see Figure 3) and two different thresholds, of indifference and preference, can be used to reduce the impact of the evaluation uncertainty on the result.

In some multiple criteria methods a critical performance of an alternative on a specific criterion, when other alternatives present good or very good performances on the same criterion, could be underestimated (because of the compensatory effect). In ELECTRE III discordance thresholds can be introduced to avoid this risk, but they require a careful attention to the meaning of the criteria and the used scales, in order to distinguish critical and good evaluations.

The different importance of each criterion can be defined by coefficients that represent an organisation policy in relation to a decision situation. Different decisional scenarios can be hypothesized, in order to collectively analyze the sensitivity of the results to the relative importance of the constructed criteria.

When the procedure has “guaranteed” that some alternatives are acceptable in terms of effectiveness and “not so expensive”, the life cycle costs have to be analysed and evaluated from both the points of view of the company and the client. We developed a model for ELECTRE III in which we included criteria that calculate/estimate all the costs: Research & Development, Investment (low rate initial production, production, deployment), Operating (Marginal Operating Costs plus Mission Peculiar Costs) and Disengagement costs. The model was examined with the company areas who are involved at different levels in the life cycle costs argument (Logistic Support, Business Development, Preliminary Design and Product Scenarios), in terms of formal validity and consistency with the internal procedures of the company. The application of ELECTRE III produced results that are limited to the company’s vision of the problem. In order to test their robustness and reliability, the company will test the complete model with the more interested and involved clients.

6 Conclusions

A client's involvement in the initial phase of an engineering design process is always important and has to be carefully managed. The temporal horizon to produce an innovation in the aeronautic sector always involves a difficult definition of the client’s needs and some risks in translating the needs into formal requirements. The analysis and comparison of some draft solutions is an effective approach to understand the client’s point of view and the general structure of his/her preference system. However, this approach requires time to elaborate understandable technical solutions, analyse them with the client and elaborate new solutions for a new collective analysis, in a learning cycle.

Complexity and uncertainty elements can have a negative impact on the problem definition in some decision situations, especially when different, and sometimes conflicting, points of view require the involvement of specific experts from the client’s organization. The implication of various actors is not easy, but remains a mandatory course of action if we wish to obtain a decision that is accepted collectively.

A structured procedure can support the acquisition of the different points of view and their translation into mathematical models and then into product requirements, and can prevent, or at least control, ambiguous specifications.

The opportunity to produce conceptual solutions in a short time (a solution requires only a few seconds of calculation time), with the guarantee of technical acceptability and specific performance levels in relation to an objective, makes communication possible and effective in the engineering design process.

Formal models that use an intelligible language introduce a positive psychological effect, in terms of a clear thinking structure and perception of the logical progress. At the same time, they facilitate the traceability of the decision process steps and results.

The integrated use of mathematical programming and multiple criteria methods can make the phase of active collaboration with the client more rigorous (no acceptable solutions are lost and the evaluations can be documented and used consistently) and efficient, because all the structured and partially structured indications can be introduced into the models and transformed, by means of the methods, into information for the decision process.

The MBDD was satisfied with this new approach to the client’s involvement in the engineering design process, and subsequently requested the support of our group in the analysis of a more complex situation. In some innovation processes, not only technological, but also organizational complexities are often present, together with uncertainties regarding the potential market of the innovative products. One of the main difficulties is creating a communication and decision space that allows the “technological” actors (i.e. the firms that are involved in the innovative project) to interact with other actors, who can express the points of view of the different end-users and their economic and organizational constraints with regards to the acceptance of the innovation and the consequent activation of new procedures or change processes.

Several individuals and/or organizations should be involved in the conceptual phase of this design process, but they have to be identified and their needs analyzed before the decision space creation. An integrated use of soft and hard Operations Research tools can facilitate the decision process by providing a logical framework (also used in Alenia Spazio, 2004 and Norese et al., 2008).

When the process is so innovative that the profiles of the clients/end users are not clearly known, an integrated use of actor network analysis and cognitive mapping approach, to acquire and organize knowledge and information elements, with mathematical programming and multiple criteria methods, to elaborate and compare possible solutions, could support the problem definition step of the design process and the creation of a communication and decision space (see for instance Norese et al., 2010).

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