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Original Article

How to use an Optimization-based Method Capable of Balancing Safety, Reliability, and Weight in an Aircraft Design Process

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ABSTRACT

In order to help decision-makers in the early design phase to improve and make more cost-efficient system safety and reliability baselines of aircraft design concepts, a method (Multi-objective Optimization for Safety and Reliability Trade-off) that is able to handle trade-offs such as system safety, system reliability, and other characteristics, for instance weight and cost, is used. Multi-objective Optimization for Safety and Reliability Trade-off has been developed and implemented at SAAB Aeronautics. The aim of this paper is to demonstrate how the implemented method might work to aid the selection of optimal design alternatives. The method is a three-step method: step 1 involves the modelling of each considered target, step 2 is optimization, and step 3 is the visualization and selection of results (results processing). The analysis is performed within Architecture Design and Preliminary Design steps, according to the company's Product Development Process. The lessons learned regarding the use of the implemented trade-off method in the three cases are presented. The results are a handful of solutions, a basis to aid in the selection of a design alternative. While the implementation of the trade-off method is performed for companies, there is nothing to prevent adapting this method, with minimal modifications, for use in other industrial applications.

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1. Introduction

The Product Development Process (PDP) comprises numerous steps or phases, described somewhat differently by different authors, as stated in Unger and Eppinger [15]. Various authors present different models of the design process [2,11,14]. Companies also have their own views of how to proceed in the process, although most processes have great similarities [4]. Staged processes were popular for decades because of their controlled design structures [15]. In this paper, the term “early design phases” means the time span from late in concept development to midway through system level design, as presented in Fig. 1. Aircraft design is a complex process that involves many different disciplines to obtain a holistic

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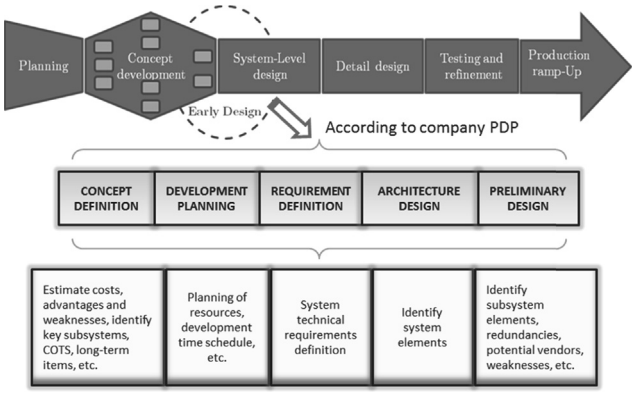

Fig. 1 – Activities performed within early design phases according to the company's Product Development Process (PDP). COTS, XXXX.

approach; many aspects need to be balanced against each other, e.g., safety requirements, reliability goals, and performance specifications. However, while system safety and reliability analyses might begin early in the design [12], with the aim of increasing confidence in the chosen design and avoiding taking decisions regarding design changes at a later stage (which means higher costs). It is in a later phase of the design that most of the system safety and reliability work is done. These analyses use a large range of methods, e.g., Fault Tree Analysis [7,8,12,13,16] and Reliability Block Diagrams [7,8,16]. Typically, targets related to economic performance and those related to safety performance may very well be in conflict, so that the final choice is necessarily a compromise solution [3]. These trade-offs are handled by different optimization techniques. Optimization problems with multiple contradictive targets (the improvement of one target come at the expense of another) are known as multi-objective optimization problems. Finding a single solution in such cases is very difficult, if not impossible. In general, for a problem with m objective functions, the multi-objective formulation can be as follows: minimize/maximize $f_i(x)$ for $i = 1, 2, \ldots, m$ [1,15]. Many algorithms have been purposed over the years, one of which is the Genetic Algorithm [1,3,9,10,17]. Trade-offs between targets in early design phases might improve the reliability and system safety *baseline* and avoid late changes due to safety or reliability issues. In this paper, the term *baseline* means the preliminary results of system safety and reliability objectives, based on allocated values. One method—Multi-objective Optimization for Safety and Reliability Trade-off (MOSART)—that is able to handle trade-offs such as system safety, system reliability, weight, and cost has been developed by Johansson [4] and implemented at SAAB Aeronautics.

The aim of this paper is to demonstrate how the implemented trade-off method (MOSART) might work in practice to aid the selection of design alternatives.

Aspects considered in this paper concern what can be learned from analyzing system architectures and what can be gained by applying the method. Three cases are considered to highlight those aspects. One case is when the implemented method is tested on a fuel system concept in order to find a balanced combination of vendors for the system's elements. Another case is when several architectures are compared from system safety, reliability, cost, and weight aspects. The last case is to investigate the possibility of finding an optimal solution for the design vector while balancing several safety objectives against the cost and weight objectives, when an additional system safety objective has been introduced.

2. Materials and methods

2.1. Method review

The core of designing is reasoning from function to form. One of the most important tasks of design methodology is to indicate how design processes should be arranged so that they inevitably lead to reliable, effective conclusions and are efficient as well, according Roozenburg and Eekels [11]. According to the company's PDP, the steps shown in Fig. 1 are performed in early design phases. Design problems are always set within certain limits or constraints. One of the most important limits is that of cost [2].

It is in the early phases of the design process that most of the cost is committed. Within the timespan of the design process, knowledge about the problem is gained but the design freedom is lost due to the design decisions made during the process. The characteristics of design evolution with time are illustrated in Fig. 2. A generic objective, or measure of value for the design process (for instance *knowledge* or *freedom*, as well as *cost committed*), is displayed as a random variable with a time-dependent probability distribution. As the design evolves, according to Mavris and DeLaurentis [7], it is desirable to shrink the variability of this objective, as well as shift its mean to more desirable levels (a *lower the better* scenario is depicted in Fig. 2). Nowadays, in other words, it is essential within the design of new products to increase awareness (knowledge) early in the design phases and keep the design decisions (freedom) open as long as possible, and with that

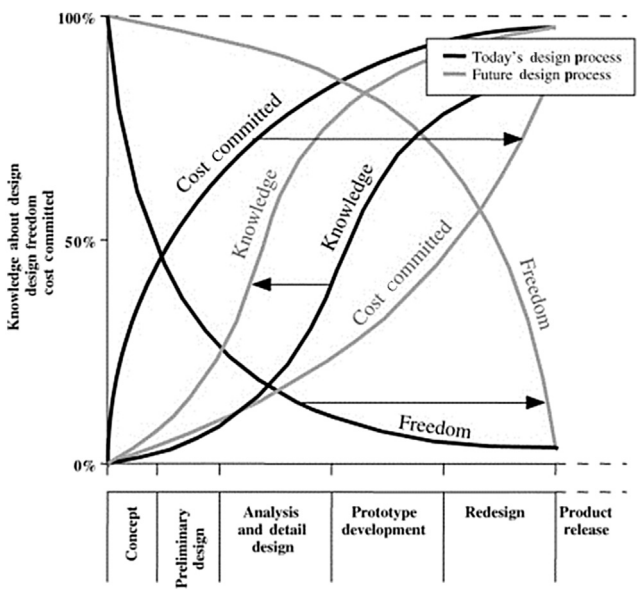

Fig. 2 – Design evolution according to Mavris and DeLaurentis [7].

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also keep down the allocated costs. A method that can make a change possible in a desired direction, by balancing contradictory objectives, so as to aid the decision-maker in early design phases, has been developed and implemented at SAAB Aeronautics—MOSART.

MOSART [4] is a general three-step method, shown in Fig. 3, that is able to balance several objectives of varying mathematical nature that have high impact on design choices. However, the formulation influences the optimization technique used to solve the optimization problem. The chosen strategy is to use an aggregating method to convert the multi-objective optimization problem into a single objective problem. The weighted sum approach [1] combines different objectives using certain weights w_i, $i = 1,\ldots, M$ (where $w_i \in [0, 1]$ is the weight of the M-th objective function and M is the number of objectives), and merges them into a single function. The weighted sum of the objectives can only be used after normalizing the objective values. Thus, the objective function is:

$$f(x) = \sum_{i=1}^{M} w_i \times f_i(x) \quad (1)$$

The general form of the optimization problem now is minimize/maximize $f(x)$. Due to the nature of the optimization problem, the optimization technique used for its solution is based on a Genetic Algorithm [3,5,17]. The optimization is performed multiple times, for several relative estimated importance vectors w, since when using this preference-based strategy (weighted sum), the optimal solution obtained is highly subjective to the particular user. Fault Tree Analysis [7,8,12,13,16] is used to model system safety and a Reliability Block Diagram [7,8,16] is used for to model reliability.

2.2. Case study

The case study is on an aircraft's fuel system. Several concepts are investigated. The desired solution is the one with the lowest probabilities of occurrence for the system safety objective, the highest probability of occurrence for reliability, and the lowest values of cost and weight (Fig. 3). As these objectives are naturally contradictory, there seldom exists one design that meets all these goals. In this paper, it is assumed that the best benefit of such an analysis might be obtained when there is some input data for all chosen objectives, while still allowing room to change the architecture design without entailing huge costs (Fig. 2). It is difficult to decide beforehand when the best results of such an analysis will be achieved [15]. In the concept definition phase (Fig. 1) it was very difficult to collect data about all the objective costs, weights, potential vendors, *failure rates*, or *mean time between failures*, etc. For instance, these kinds of data were available (though incomplete) sometime in the timespan between the end of configurations Number (No.) 1 and No. 2 (Fig. 4) of the fuel system. This situation might differ from project to project and from company to company. Therefore, the analysis is performed within the architecture design and preliminary design steps, according to Fig. 1.

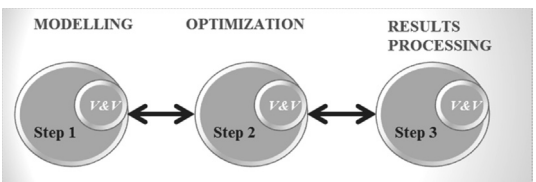

Fig. 3 – Theoretical method (MOSART). MOSART, Multi-objective Optimization for Safety and Reliability Trade-off; V, XXX.

2.3. Fuel system description

The general layout of the fuel system may consist of one or more boost pumps that feed the engine from a collector tank (for instance T1 in Fig. 4). The collector tank is replenished by a fuel transfer system, which pumps fuel from the source tanks (T2, T3, and T4 in Fig. 4).

The system may be pressurized to avoid spontaneous fuel boiling at high altitude and cavitation in pumps, or to provide the means for fuel transfer. An aircraft's fuel system may consist of several subsystems, according to the functions to be provided, such as: Engine Feed System, Auxiliary Power Unit Feed System, Fuel Transfer System, etc.

In the Architecture Design step (Fig. 1) short loops are performed, providing slightly different architectures of the fuel system. Each of these architectures is analyzed and reviewed from a system safety and reliability standpoint; simulations and calculations are performed for several performance parameters, and the proposed architecture is updated according to new data. Three different architectures, focusing on providing fuel feed to the engine and auxiliary power unit and heat sink for the engine's electronic control unit (ECU) are used as examples in this paper and shown in Fig. 4.

2.4. Problem formulation

The aim is to achieve a balance between the system safety, reliability, cost and weight targets. A solution x is a vector of n decision variables: $x = (x_1, x_2, \ldots, x_n)^T$. For instance, a vector of design variables, x, is used (for the sake of simplicity, in this case study it is called design vector), which can adopt a number of integer values, where each integer represents a different alternative. These alternatives are the system elements, e.g., components/items in the system. Each alternative includes data about the selection of suppliers, costs, weights, failure rates, or mean time between failures. The system safety objective might be different depending on the failure conditions analyzed, for instance loss of fuel feed to the engine, loss of cooling to ECU, etc. The reliability objective is considered to be the full functioning of the respective subsystem of the fuel system (feed fuel to the engine, provide ECU cooling, etc.). Aspects considered in this paper concern what can be learned from analyzing one of the architectures presented in Fig. 4 and what can be gained by applying the method presented in Section 2. Three cases are considered to highlight those aspects:

- *Case A*: Analyses the safety and reliability, weight and cost objectives of one architecture.

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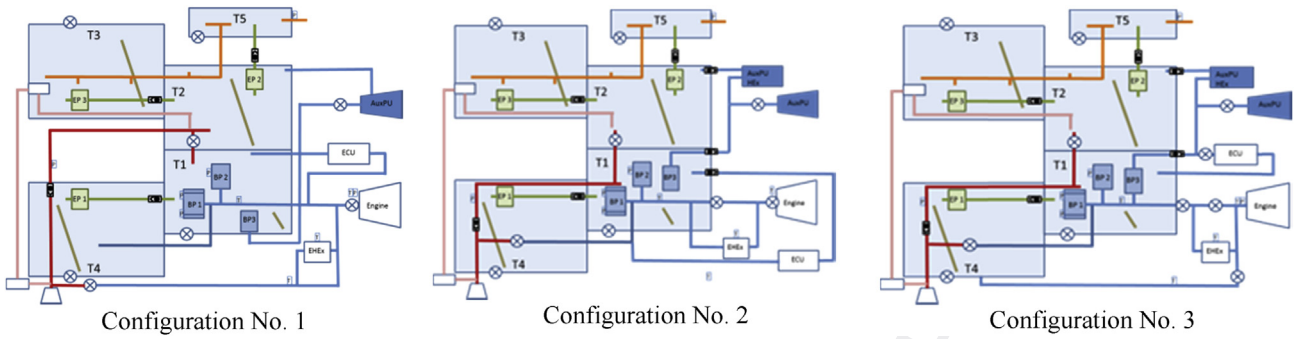

Fig. 4 – Fuel System preliminary architecture (Configuration No. 1, No. 2, and No. 3). AuxPU, XXX; BP 1, XXX; BP 2, XXX; BP 3, XXX; ECU, electronic control unit; EHEx, XXX; EP 1, XXX; EP 2, XXX; EP 3, XXX; No., number; T1, XXX; T2, XXX; T3, XXX; T4, XXX.

First, the implemented method is tested on a fuel system concept in order to find a balanced combination of vendors for the system's elements. The analysis is performed on configuration No. 1, in Fig. 4. The system safety objective is no fuel supply to the engine. This event causes engine disturbances and loss of aircraft and is thus one of the most important failure conditions to analyze. The reliability objective is to provide fuel feeding to the engine.

- *Case B*: Analyses the safety and reliability, weight, and cost objectives of three architectures.

Second, this paper investigates what can be learned when comparing several architectures from system safety, reliability, cost, and weight standpoint. The analysis is performed repeatedly on configurations No. 1, No. 2, and No. 3, as shown in Fig. 4. All the objectives are maintained as in Case A.

- *Case C*: Analyses multiple safety objectives and one reliability, weight and cost objective of one architecture.

Third, an additional system safety objective has been introduced to investigate the possibility of finding an optimal solution for the design vector while balancing several safety objectives against the cost and weight objectives. In everyday engineering practice, a system safety engineer has to investigate several failure conditions causing the same output (with the same criticality). The system safety objectives are no fuel supply to APU during engine flame out and loss of cooling to ECU. Both events will cause engine disturbances and loss of aircraft. The reliability objective is to provide fuel supply to APU and is of interest from a mission reliability standpoint.

3. Results

The results obtained are a handful of design solutions (in the form of design vectors) regarding the choice of vendor for each piece of equipment in order to balance the objectives, shown for the analyzed cases. A total of 11 potential vendors for fuel system equipment are taken into consideration. The company itself is one of the vendors for installation components and some of the items. For each item, weight and a general failure rate are provided. The design vectors consist of several positions (for instance, 29 positions in Case A), each position taken by an element of the fuel system and consisting of integer values between 1 and 11, representing the identified potential vendors.

- *Case A*

The results can be visualized to highlight the gain or loss of each objective compared with the requirements or goals for the respective objective, as shown for instance in Figs. 5A and 5B. The black stamps in Fig. 5A indicate the results that do not meet the requirement/goal for the respective objective, while the white stamps show the gain when the results of each objective are compared with the requirement/goal. The top stamp-diagram in Fig. 5A represents the cost objective, while the bottom stamp-diagram represents the safety objective. In Fig. 5B the top stamp-diagram represents the weight objective and the bottom diagram stands for the reliability objective. In Fig. 5A, the safety objective results for the 20th solution in the analysis can be read on the left vertical scale, while the cost objective results can be read on the right scale. Similarly, in Fig. 5B, the reliability objective results can be read on the left vertical scale and the weight objective results on the right scale.

- *Case B*

In this case, the objectives are identical with those of the previous section. However, the analysis is repeated for all three architectures shown in Fig. 4 and the solutions of each configuration are compared for cost, safety, reliability, and weight objectives in Fig. 6. The results suggest that configuration No. 3 (green line, triangle dots) is better than configurations No. 1 (blue line, rhomb dots) and No. 2 (red line, square dots) from all objective standpoints. The safety and reliability objectives have almost identical solutions for configurations No. 1 and No. 2, which means that from the safety and reliability standpoint there were no improvements in safety or reliability of design between these two architectures, except in solution No. 3.

- *Case C*

The solutions might be visualized and filtered using a parallel coordinate plot, as shown in Fig. 7. The solution

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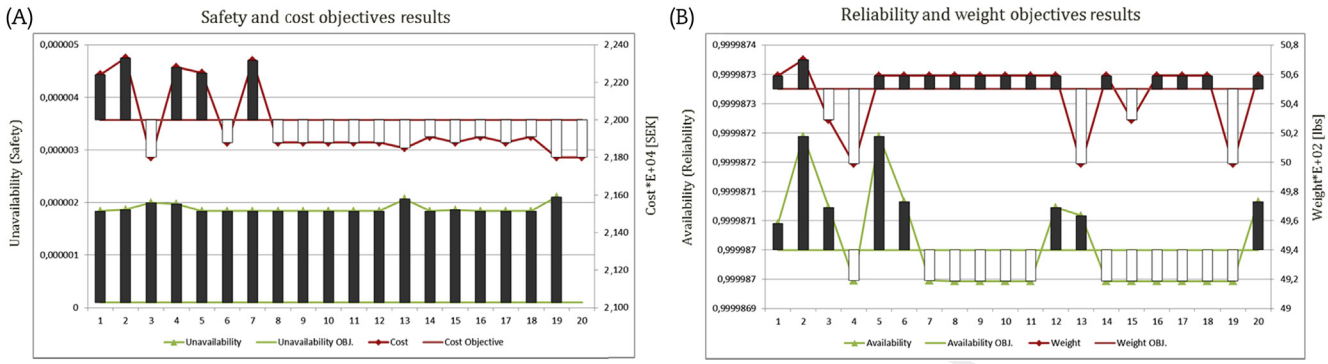

Fig. 5 – Objectives compared with requirements/goals. (A) Safety and cost objectives compared with the requirements/goals. (B) Reliability and Weight Objectives compared with the requirements/goals. OBJ., objective; SEK, XXX.

suggested (the blue line) is No. 11, in which the best balance between the objectives is achieved (objectives considered equally important). The suggested vendors for all elements included in the analysis are pointed out, in order to balance the cost, system safety, system reliability, and weight objectives.

4. Discussion

From the results in Case A, the main insight is that the design should be changed in order to be closer to the system safety requirement, since none of the solutions were even close to this requirement, while there were solutions that met all the other requirements/goals. This might be achieved by finding other vendors for the system elements, provided that this is possible from other standpoints, e.g., technological, political, financial, etc., or by changing the system architecture (more redundancy, diversity, etc.). However, the results shown in Fig. 6 suggest that this was not the case. Changes were made in the architecture of the fuel system concept (configuration No. 2), but mainly due to other characteristics. The main difference in architecture was to change the main boost pump from one using a hydraulic solution to an electrically driven pump. The new solution was lighter and cheaper and the results show an improvement in these objectives (Fig. 6). The failure rates, however, were similar, and what is gained from a slightly better failure rate for the electrical pump is balanced out by introducing a few new elements (valves) with their potential failures. The new solutions thus do not indicate an improvement in the safety and reliability objectives for configuration No. 2. Configuration No. 3 changes the architecture of the system by introducing a triple redundancy for feeding fuel to the engine, cooling the ECU, and feeding fuel to the APU, as well as reducing, as much as possible, the number

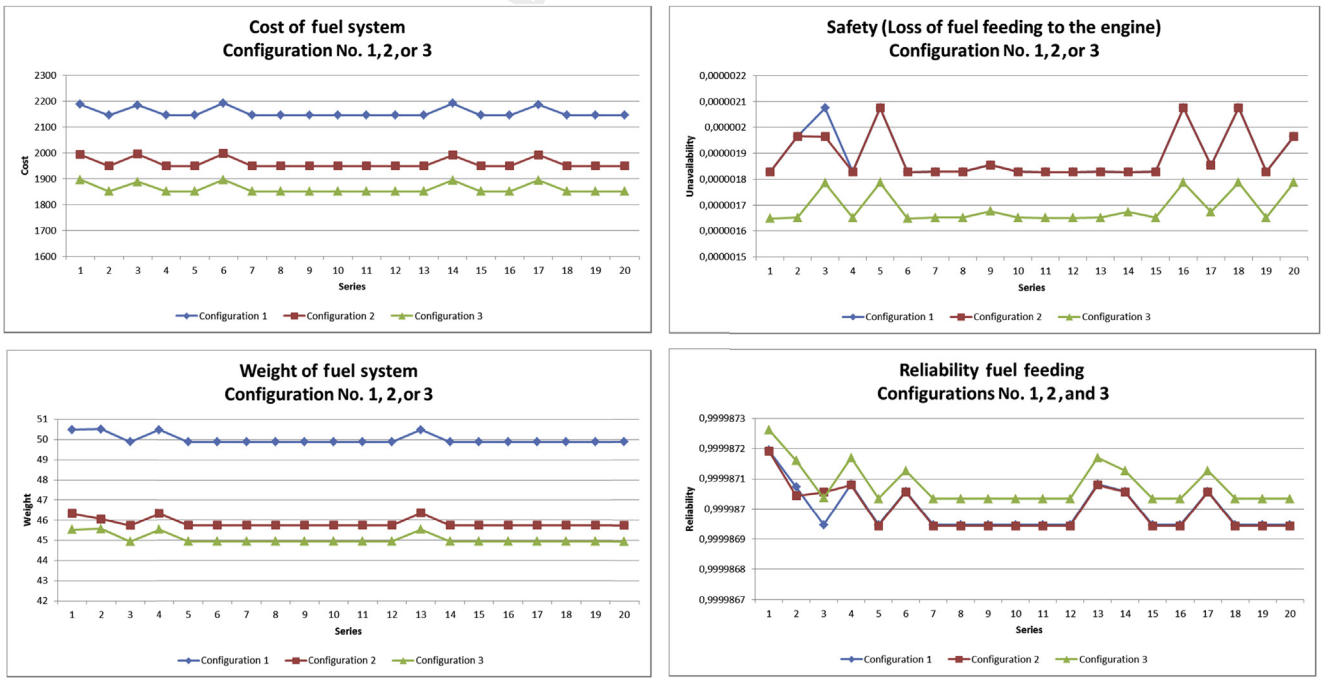

Fig. 6 – Cost, safety, weight, and reliability objectives for all three fuel system architectures (Fig. 4).

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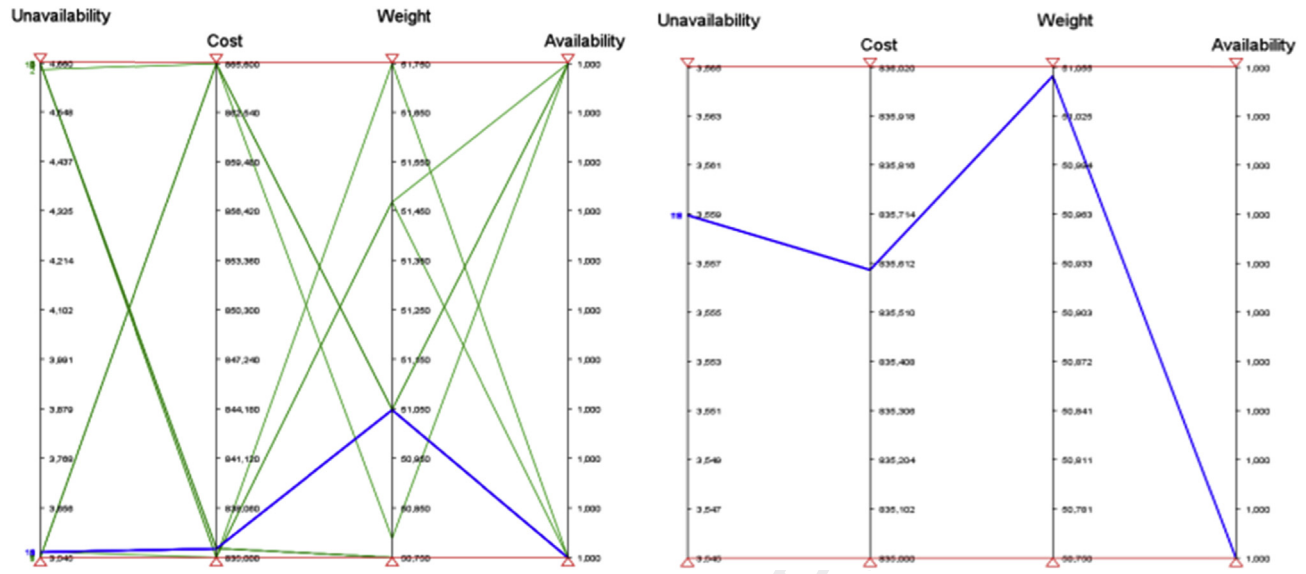

Fig. 7 – Visualization and sorting of solutions in a parallel coordinate plot for multiple safety objectives.

of installation components outside the fuel tanks to reduce the risk of leakage outside the fuel tanks. Although the system safety requirement is still not achieved, a clear improvement in all factors under consideration can be observed in the results presented in Fig. 6, as well as for the reliability objective.

Fig. 7 shows another way of visualizing and sorting the results. However, Case C might be the case most likely to be used in practice. The failure conditions and hazards analyzed in a system safety analysis such as Functional Hazard Assessment and Preliminary Hazard Analysis [4,12] are assigned early in the design, the criticality classification, and the maximum allowed probability of occurrence (safety requirements). At some point, the safety requirements might even be in contradiction. For example, introducing a heat exchanger, purchased from a certain vendor, for the fuel feed line, might decrease the probability of loss of ECU cooling, but increase the probability of engine disturbances due to clogging. Using multiple safety objectives clustered by a certain safety requirement (e.g., 1.0E-07 failures/flight hours for a catastrophic event) gives the opportunity to analyze the system at a higher level, as a whole (e.g., noncombat loss rate might be an overall safety objective). The same reasoning goes for using multiple reliability objectives. Combining, e.g., several mission reliability objectives, it is possible to trade off aircraft reliability to perform several different missions against targets like safety, cost, and weight.

The analysis presented in this paper was performed not during the time line presented but afterwards, in later phases of the project. The architectures (Fig. 4) included in this paper were developed within the time span of 3 months with a few weeks in-between. One challenge was to collect the information and reasoning involved in the decision-making backwards, when the project itself was moving forward. However, the design process used iterative development [11], rather than a straightforward one, as shown in Figs. 1 and 2. The design process during the analyzed period was characterized by short loops focused on different properties of the design (three architectures within a time span of 3 months). These loops comprise sequences of steps ending with a comparison between the obtained results and the desired results. The knowledge gained in one loop is fed back into the process of design proposal, formulation of problem, and requirements. As the results also show, in one loop, not all properties were considered at the same time. For example, in one loop of the case study, the designers focused on decreasing the weight of the system, disregarding the influence of system safety, and reliability. System safety as a property of the system was considered in another iteration, etc. This can be explained by aspects such as specifics of the project and organization (large project, different departments working with different systems and subjects, the physical location of the designer teams, etc.). By using MOSART, several different properties of the design (for instance safety, reliability, weight, and cost) were included in one loop, covering larger parts of the solution space or, if desired, decreasing the number of iterations. The development of the design still has the iterative, somehow spiral-like character, but with another distribution of knowledge diagram, as shown in Fig. 2. The same knowledge is gathered earlier in the design phases, when the design freedom is higher and changes are less expensive. Furthermore, the specific design phase might be somehow shortened, either by decreasing the number of loops needed to gather the same experience, or by gathering more knowledge in a shorter time.

This paper assumed (based on experience) that the best benefit of such an analysis might be obtained when there is some input data for all chosen objectives, while still being able to change the architecture design without entailing huge costs. It was first possible to collect input data for all chosen objectives, according to the company's PDP, shown in Fig. 1, in the architecture design phase (within the concept phase in Fig. 2). As the design progressed, the input data changed. Even if the design freedom decreases, MOSART might still be used

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within the whole preliminary design phase and in detail design (Fig. 2) to motivate trade-offs between targets (for instance safety, reliability, weight and cost). With hindsight, this timespan might be between the architecture design phase within the concept phase (Fig. 1), and the end of the detail design phase.

Traceability is a very important property, especially within the field of aircraft design, in which it is not unusual for the time between new aircraft models to be around 20 years. The improvements in the solutions can be followed all the way through the embodiment design by comparing the architectures from different standpoints, as shown in Fig. 6. The design loops for new similar products might be further shortened by avoiding potential pitfalls highlighted by the usage of MOSART.

In conclusion, the aim of this paper was to demonstrate how the implemented method (MOSART) might work in practice to aid the selection of a design alternative. The main insights from and engineering standpoint regarding the three analyzed cases are:

- *Case A*: the differences between all results and the safety requirement were substantial for configuration No. 1, suggesting a change in fuel system architecture rather than a change in vendors.
- *Case B*: configuration No. 3 is better than the other system architectures from all objective standpoints, but the results also reflect improvements made in each configuration.
- *Case C*: the system has been analyzed as a whole and one solution was pointed out when using multiple safety and reliability objectives.

With hindsight, it might be concluded that the use of a trade-off method (such as MOSART), as shown in this paper, could:

- facilitate the system architecture as well as the system element selection process and increase the probability of choosing the best concept,
- allow the use of multiple safety or reliability objectives, clustered by a safety or reliability requirement, yielding the opportunity to analyze the system at a higher level, as a whole,
- increase understanding of how the achievement of one objective is traded off against another,
- shorten the loops within the design process or shorten the design process,
- provide good traceability of the steps in concept and embodiment design and provide feedback for decision-makers.

While the implementation of the trade-off method is performed for companies, there is nothing to prevent adapting it, with minimal modifications, for use in other industrial applications.

Conflicts of interest

Q4 The authors have nothing to disclose.

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Acknowledgments

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