INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

VALUE MODELLING IN AEROSPACE SUB-SYSTEM DESIGN: LINKING QUANTITATIVE AND QUALITATIVE ASSESSMENT

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Abstract

The paper presents a prototype of a value model where engineering design teams can play with cost and value data in a semi-structured way. In particular, the value model serves to facilitate communication of multidimensional information during preliminary design analysis and to visualize such information in a unique environment. The model first automatically generates, from the output of a computer-based simulation, a quantitative assessment of manufacturer costs and customer cost savings of a set on different configurations of the same design concept. Second, it couples to the results a qualitative assessment of concept risks and product and process commonalities. Third, it allows an assessment of the concept impact on the customers' "ilities" (maintainability, survivability, scalability, flexibility). The model has been developed in collaboration with an aerospace sub-system manufacturer and it ultimately aims to enable the maturation of the knowledge about cost and value aspects among the design team since the preliminary stages of design.

Keywords: Decision making, Early design phases, Visualisation, Evaluation, Value Modelling

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Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. nn: Title of Volume, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

Any design process is built upon a series of actions and decisions that transform the initial ideas into the final product. Traditionally when a design project is started several design concepts are formulated with the intent of satisfying the needs of the targeted customers. However not all the concepts will be ultimately delivered, instead a series of design decisions will be taken in order to down-select the number of possible concepts. In complex development processes, such as in aerospace product development, such concept down-selection is strongly influenced by the requirements cascaded down from the higher level customers or from the internal stakeholders that drives the selection of the most requirements-fulfilling concept (Isaksson et al., 2013).

Despite recognizing the importance of such drivers for decision-making, research in aerospace product development has highlighted how requirements-centred decisions approaches are weak in driving decision making in the preliminary design stages. This is particularly true in those design contexts that require a conjunct design and technology development effort (Eres et. al., 2014). This happens because companies, to reduce development cycles and times-to-market, "have to start working ever earlier in a programme context, long before mature requirements from the super system are made available to them" (Eres et. al. 2014, p.65), and also because some requirements need to be first validated trough engine rig test and engine flight test before being approved.

Collopy and Hollingsworth (2009) where among the first to formalize the need to move a step forward from the requirement fulfilment approach. They described the need to adopt a Value-Driven Design perspective in early design, to base the decision on an assessment of the Surplus Value that a design concept would generate rather then on requirements fulfilment. From the stand point of a sub-system/component manufacturer Bertoni et al (2013) highlighted that "value models" are needed in preliminary stages of aerospace component design, to enable more informed trade-off decisions amongst different design concepts from a multidimensional and stakeholder-oriented perspective.

Computer-based product simulations play a critical role at this stage in verifying if the proposed concept is fulfilling the necessary performance requirements. However, technical performances are not the only information needed to take conceptual decisions. Decisions need to be made considering a wider perspective of effects that the new product would generate, such as, for instance, the assessment of the impact on customer revenues (Markish and Wilcox, 2003), the level of risk that the choice of a concept embeds (Browning and Eppinger, 2002), the production costs linked to each concept configuration (Browning and Eppinger, 2002) or the commonality of the concepts with existing platforms or technologies (Simpson, 2004). Such information is not embedded in computer-based simulations and is difficult to be expressed in a quantitative fashion to be directly coupled with an automatic calculation of the "best concept" to be selected. Informed trade-off decisions need therefore to be supported by models capable of linking both the quantitative technical performances analysis and the qualitative assessment of the value of the concept in respect of manufacturers and customers' needs (Bertoni et al., 2013).

Different existing models are nowadays in use, spanning from quantitative, simulation-driven approaches (such as Finite Element Analysis, agent-based, systems dynamics, or discrete event simulations), to purely qualitative approaches based on expert judgment, such as Quality Functional Deployment or Pugh Matrixes (Hauser and Clausing 1988; Pugh, 1991). Research in design of complex systems has highlighted that qualitative methods are primarily used as boundary objects (Carlile 2004) useful for translating knowledge between social actors surrounding a complex social and technical system, while quantitative are useful for describing the behaviour of the system modelled (Koo 2005). Efforts to merge qualitative modeling languages and quantitative simulation approaches have been spent by Koo (2005), proposing an Object-Process Network to construct models useful for knowledge sharing and formal quantitative analysis, and Bartolomei (2007) proposing a methodology for translating qualitative data into quantitative matrices for analysis. However such methodologies do not address the needs that rise when specific early design concepts are traded-off in sub-system preliminary design. When first computer-based simulations are available, current industrial practice shows that designers easily lose the link between quantitative and qualitative evaluation. The information about how much valuable is the concept under study is therefore difficult to be grasped by designers studying the performances variation given by component design modifications. Models to properly communicate the high-level systems effects of designers' decisions are missing.

Such limited awareness of product consequences increases the risk for designers to be asked for late design modifications to better address the needs, both internal and external, that raise all along the development process. Being able to link, and properly communicate, quantitative simulation-driven information with qualitative value assessment has therefore the potential of driving preliminary design analysis toward more value-aware decisions, reducing the risk of unexpected costs and time delays in the later stages of the product development process.

2 AIM OF THE PAPER

This paper presents the prototype of a value model, developed in collaboration with an aerospace sub-system manufacturer. The prototype aims to support preliminary design decision making by linking quantitative information from early concept simulation to high level qualitative product assessment. In particular, the value model serves to facilitate communication of multidimensional information during preliminary design analysis and to visualize such information in a unique environment.

The research presented in this work has been carried out using an approach based on participatory action research (Whyte et al., 1989). Empirical data have been collected through authors' participation in physical and virtual meetings. Discussions and workshops have contributed to the clarification of the problem domain, to the definition and validation of the proposed prototype.

3 VALUE ANALYSIS IN AEROSPACE PRELIMINARY DESIGN

Industrial organizations today need to be able to quickly and continually assess their value proposition, which business part are vulnerable, what is strategic and what is the core of the offer that generates value to the customer (Fine et al., 2002). When dealing with the design of products characterized by high cost, long lifecycles, high complexity, interdependencies with other systems and dynamic operational contexts, such as in aerospace product development, engineers need to deal with a very wide set of criteria that need to be somehow assessed to provide a support for decision making (Bertoni et al., 2013). In the literature, there has been effort to identify the different aspects of value in the domain of engineering design: Value Engineering (Park, 1999), TradeSpace exploration (Ross et al., 2004), and Value Driven Design (VDD) (Collopy and Hollingsworth, 2009), all aim to introduce a more value-oriented approach to the design of complex systems.

In the specific case of aerospace product development, system engineering (INCOSE, 2006) literature has highlighted how value is also determined by the capability to maintain or improve the system functions in the presence of change (McManus et al. 2007). TradeSpace exploration (Ross et al., 2004) considers customer value to be embedded in the customer process context and utilizes "ilities" to evaluate the system robustness under changing process conditions using criteria such as survivability, adaptability, flexibility, scalability, versatility, modifiability and robustness. The Epoch framework proposed by Ross et al. (2008) allows the systematic creation of TradeSpace model(s) to quantify these "ilities". Other evaluation methodologies do exist, such as Real Options for flexibility (Saleh et al, 2003), but cover just a few of these criteria. Furthermore, Steiner and Harmon (2009) proposed an extended model of value, adding a new layer of "intangibles". Intangibles are associated with knowledge, emotion and experience, dimensions that cannot be experienced by the customer before using the product.

In such a context, in order to provide "a framework against which methods, processes, and tools can be assessed" Collopy and Hollingsworth (2009, p.2), have proposed the concept of Value Driven Design. Accordingly to the Value Driven Design Program Committee, VDD is an "improved design process that uses requirements flexibility, formal optimization, and a mathematical value model to balance performance, cost, schedule, and other measures important to the stakeholders to produce the best possible outcome" (AIAA, na). Current VDD literature has largely focused on quantitative assessment approaches (see, for instance, Castagne et al. (2009) and Cheung et al. (2008). However, some authors (e.g. Monceaux and Kossmann (2012) and Soban et al. (2011)) have perceived VDD as having the potential to transform into a formalized design process. In this sense, an explicit step towards establishing a consistent VDD methodology has been proposed by Monceaux and Kossmann (2012), stressing the importance of using a greater degree of intangible and non-economic criteria for concept assessment. Given the relative novelty of VDD theory, many questions still need to be answered and issues solved to allow a large-scale application of this approach. Such challenges are summarized in the VDD research agenda (Soban et al. 2011), underlining, amongst other things, the importance of studying how to incorporate VDD into existing frameworks, creating new methods and tools to enhance the execution of a VDD formulation and to visually display and rationally analyse information for decision making.

3.1 Value Analysis in preliminary design of sub-system components

During product development, the use of a stage-gate process (Cooper 2008) is widely adopted as industrial practice (Johansson et al. 2011). In aerospace component design, preliminary design decisions are strongly driven by requirements fulfilment. Criteria such as High/low cycle fatigue, limit/ultimate load capability, hail ingestion, strength and stiffness, corrosion, oxidation and creep are examples of the basis for evaluation for a specific concepts (Gustavsson, 2006). A main limitation of such practice is that potentially valuable solutions tend to be neglected because the focus on technical, requirement-derived, performances, does not allow the designers to understand the value of a solution at system level. Targeting lifecycle commitments and a wider stakeholders perspective, these "traditional" dimensions need to be further complemented by criteria able to assess the "goodness" (Cheung et al, 2008) of a design alternative from a system and lifecycle point of view.

Previous work on value assessment and decision making in aerospace preliminary design, has proposed a set of criteria to be considered in early design trade offs (Bertoni et al., 2011) and has highlighted the need for sharing of heterogeneous and dispersed models across the extended enterprise, not neglecting the risk for such models to raise security, trust and contract issues amongst supply chain partners (Bertoni et al., 2011). To address such issues Isaksson et al. (2013) have proposed a value-driven design process to define a common and sharable Value Creation Strategy, meant to drive the very early development of aerospace components before the requirements are signed. Concurrently research has been run to analyse how such information can be communicated and visualized to enhance the awareness of the multifaceted aspects to be considered in preliminary design (Bertoni et al., 2013b), and how the reliability of the information can be assessed during decision making gates (Johansson et al., 2011).

Despite these recent research efforts on sub-system design value analysis, few applied examples of real industrial cases are available in literature, especially focusing on the integration of qualitative and quantitative aspects in a unique model. An attempt to merge such kind of information, not dealing with value analysis but with sustainability and environmental impact, is given by the work of Bertoni, Hallstedt and Isaksson (2014), combining strategic sustainability assessment and a simplified net present value estimation. However such work deals only with predefined sustainability criteria not encompassing a wider "value perspective" as for the value model proposed in the paper.

4 VALUE MODEL PROTOTYPE FOR A TURBINE REAR STRUCTURE

This section presents the description of the value model prototype that has been developed in collaboration with the aerospace sub-system supplier. A real industrial example of the assessment of a turbine rear frame component has been adopted as reference case to develop the value model.

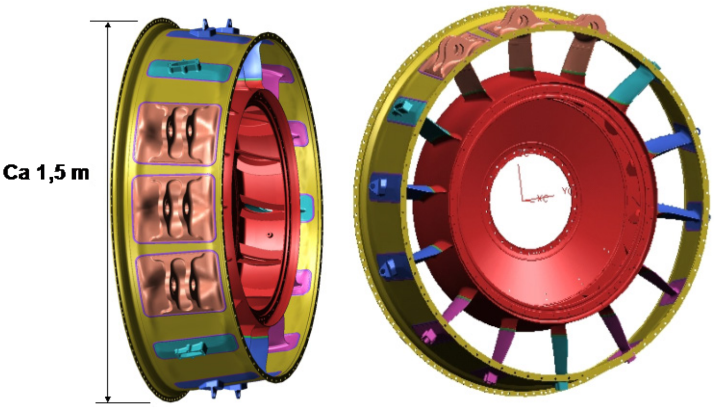

Figure 1. Simplified CAD representation of a turbine rear structure

The turbine rear structure (TRS) (figure 1) is an engine component whose main functions are to transfer different loads and to redirect the outgoing flow.

The development of the value model started with the identification of a set of aspects that needs to be considered in preliminary design decision-making. Based on previous research and on the industrial observation a framework of reference for value assessment as been defined. This framework, defines the category of value aspects in consideration of the As-Is situation, the To-Be situation and an ideal situation.

The framework, shown in figure 2, divides the value aspects as related to the manufacturer side (product/production cost, commonality, risk, and requirements fulfilment) and to the customer side (ilities, operational performances, and intangible values). The prototype at this stage of development focuses only on the part of the value model framework dealing with the assessment of the industrial value from the manufacturer side and the assessment of the tangible value from the customer side. Further development of the value model aims at an integration of the intangible aspects into the model.

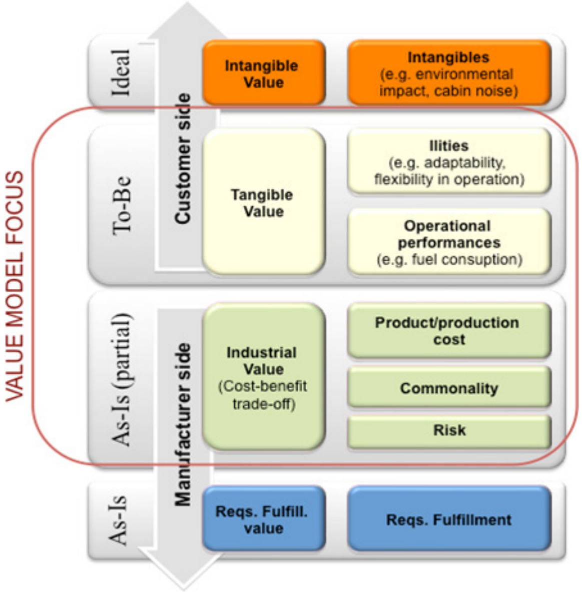

Figure 2. Framework of reference for the value model

Given such limitation the value model provides 5 different types of outputs dealing respectively with product/production cost, commonality, risk, operational performances and ilities. Such outputs are different in nature, some of them are quantitatively and economically assessable, while others are more difficult to be estimated in monetary terms. Figure 3 shows a schematic visualization of the structure of the output, dividing the criteria that have been qualitatively or quantitatively assessed.

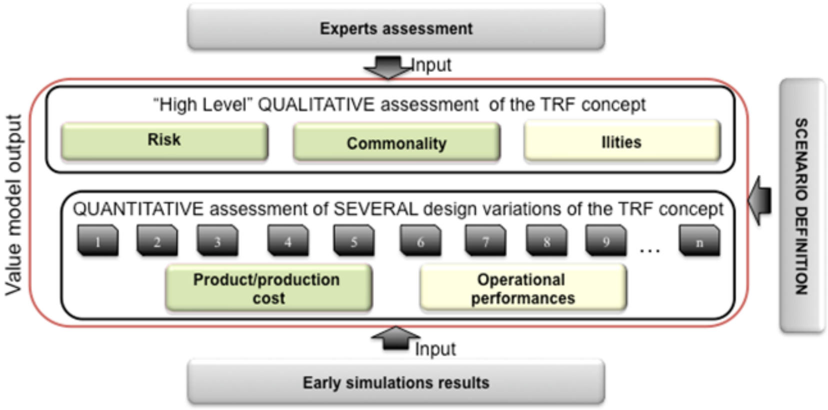

Figure 3. Output structure of the proposed value model prototype

The qualitative assessment focuses on risk, commonality and ilities. Such assessment is based on expert judgement following the methods described in sections 4.1. This part is defined as “high level” qualitative assessment since it deals with the evaluation of a concept as a whole, without going deep into the details of the geometry of the component. On the contrary the quantitative assessment is based on the input data given by the early computer-based simulation results. In the example of the TRS such analysis has focused on a number of design variations of the same TRS concept, embedding an analysis of the different impacts that changes in shape or geometry of the TRS generate.
The value model gives therefore output at two different levels of detail: “high level” qualitative output, useful to make trade-off between different concepts; and “low level” output, useful to analyse the economical performances of the possible configurations of the same concepts, thus to identify emerging potential highly valuable concept configurations.

4.1 Qualitative assessment

The qualitative assessment is based on expert judgment and consist in the evaluation of the areas: Risk, Commonality and Ilities.

4.1.1 Risk assessment

The risk assessment is built on a list of questions grouped in 5 main categories of risks, respectively: Technology Risk, Product/Manufacturing risk, System Level/Engine Architecture Risk, Risk of Potential Revenue Erosion and Operational Risk of potential escalating expenses. The last two categories are derived from Willard (2012), while the first three have been defined on the basis of what emerged in the empirical study. The model proposes a list of standardised statements for each category of risk, those have to be considered as guidelines and ad-hoc statements could be added based on specific product development projects. In the prototype 27 statements have been considered as the base for the assessment of the TRS concept. The calculation of the level of risk is based on two factors: the criticality of the effect of the event described in the statements, ranked from 1 (very low) to 5 (very high), and the percentage of probability that such event will happen within 10 years. The product of these two factors generate an index indicating the “potential increased expenses” or the “potential revenue loss”. The indexes of potential risks are summed for each category and their impact is expressed as a percentage of the impact that would be generated by the worst scenario, i.e. if all criticalities would be set to 5 with percentage of probability to 100%. Such system of calculation allows designers’ comparison of the category of risks with higher percentage of incidence and with higher potential negative effects.

4.1.2 Commonality Assessment

The assessment of commonality is based on three main levels: commonality in technology (including material and processes), commonality in product and commonality in functionality. The designer is here asked to answer to a list of questions by using scroll-bars allowing 5 types of responses: “not at all”, “to a very limited extent”, “to a minor extent”, “to a good extent”, “completely”. After this the designer is asked to rank the relevancy of the question in a scale from 1(minimum) to 5 (maximum). For instance in the TRS example, given the question “Does the component allow the reuse of qualified welding?” the designer is asked to move the scroll bar to the desired answer and state how relevant is a question for the concept under study. Finally the overall level of commonality is calculated for each category as a percentage, given that 100% correspond to a situation in which all the questions are answered “completely” and all the relevancies are set to 5. As for the risk assessment the models provides a set of predefined questions, derived from the empirical study, to be used for commonality assessment, those should be considered as guidelines and could be modified if needed.

4.1.3 Ilities Assessment

The term “ilities” has been coined by McManus et al. (2007) in the system engineering literature to summarize a set of criteria used to evaluate the system robustness under changing process conditions. The value model builds on such definition in order to define the aspects, at system level, that impact the value generated to the customers. Four “ilities” have been used and reinterpreted from a sub-system manufacturer perspective, to represent the value generated to external stakeholders. Scalability (i.e. how easy is to scale up/down a component in case of system dimensional changes), flexibility (i.e. how flexible are the performances of the components if external parameters changes), maintainability (i.e. how easy/fast/efficient is to maintain/replace a component), and survivability (i.e. how the component behave in case of unexpected flight conditions) have been identified as relevant drivers of value. A list of questions to be answered corresponds to each “ility”. Differently from what done with commonality and risk, the ilities are assessed based on a benchmark, so a new concept is evaluated on how much is it expected to be better or worse compared to another component. Given for instance the assessment of a survivability aspect of a TRS concept such as “How the component behave in case of unexpected flight into an ash cloud?” the designers select with the use of a scroll bar a value from 1 to 7 with 1 being “much worse than the baseline”, 7 being “much better than the baseline” and 4 being “same as the baseline”. This assessment, weighted by the relevancy of each question allows designers to understand if a new concept could bring additional value to the stakeholders up in the supply chain compared to baseline.

4.2 Quantitative assessment

The quantitative part of the value model is based on the data available from an early concept simulation. Quantitative component data are used to assess the operational performances and the product cost of different configurations of the same concept. The simulation platform allows obtaining the output in a specific range of input variations of a design parameter, thus getting information about the concept performances and characteristics for specific points of the design space.

4.2.1 Operational performances

To study the benefit generated by different design variations on the operational performances of the airline, the fuel consumption of the airplane has been considered as the main parameter. Weight has a strong relation to fuel consumption, thus many efforts at component level are often focused on weight reduction. Being able to save weight on a component would most likely have beneficial aspects in terms of fuel saved. The model makes use of the information about the mass of the different design configurations and derives an estimate of the “saving per flight” generated. The model is based on the assumption that a reduction in weight on an engine component can have potential benefit on the overall weight reduction of the engine that, by consequences, can generate potential weight reduction on the whole aircraft. For this reason the model implements a system of “multipliers” expressing the relation between the reduction of 1 kg of weight in a component and the overall aircraft weight reduction. In other words the multiplier answer to the question: “how many kg of weight could be saved in the aircraft if the component would weight 1 kg less?”. The overall weight reduction is then linked to a function, which expresses the marginal saving of gallons of fuel per one kilogram of aircraft weight reduction based on the range of the flight. This calculation allows estimating the potential savings in fuel consumption linked to the choice of different concept configurations, this is done in respect to how much the concept configuration is better or worse then a baseline.

4.2.2 Product and Production costs

Similarly to what done for the operational performances, the assessment of product and production cost does not provide an absolute measurement of the product cost, instead it is based on the benchmark with a current product. This allows the designers to focus only on those cost drivers that really change comparing one design configuration to another, making it easier to assess cost variation. Two main cost drivers are identified as relevant and prone to major variations: material costs and number of operations associated with the concept. The material cost is estimated on the basis of the cost per kg of the material and of the mass of the different design configurations outputted from the simulation. A parameter indicating the average percentage of scrap from the production process is also added to the estimation.

The estimation of the number of operations related to the concept is currently not implemented into the prototype. The assessment is nowadays limited to an indication of the estimated welding costs based on thickness and length of upper and lower welds obtained from the computer-based simulation. The model uses such data in a first stage to verify which are the feasible welding methods based on technological constraints and industrial design practices. At a second stage an order of preference to the welding technology is assigned linked to an estimation of the welding cost per meter connected to each technology. Finally the model selects the welding technology based on the lower expected cost and uses such data to complement the information on the overall product cost. Despite being a first step into the implementation, merely estimating the welding cost is seen as a limited measurement for the cost assessment and research is currently undergoing to extend this part of the model to target the automatic definition of the list of operations.

4.3 Output interface

The model contains an output interface that has the goal of summarizing all the estimations and assessments run. The output interface (Figure 4) allows communicating, in a unique visualization, multidimensional information enabling the user to zoom in into specific aspects if needed. Aim of the output interface is also to provide a quick summary of the concept value assessment to easier the comparison between different concepts in decision meeting. It serves both the goal of raising discussions about concept characteristics and of giving a quick visual representation of the multidimensional value aspect to be taken into consideration.

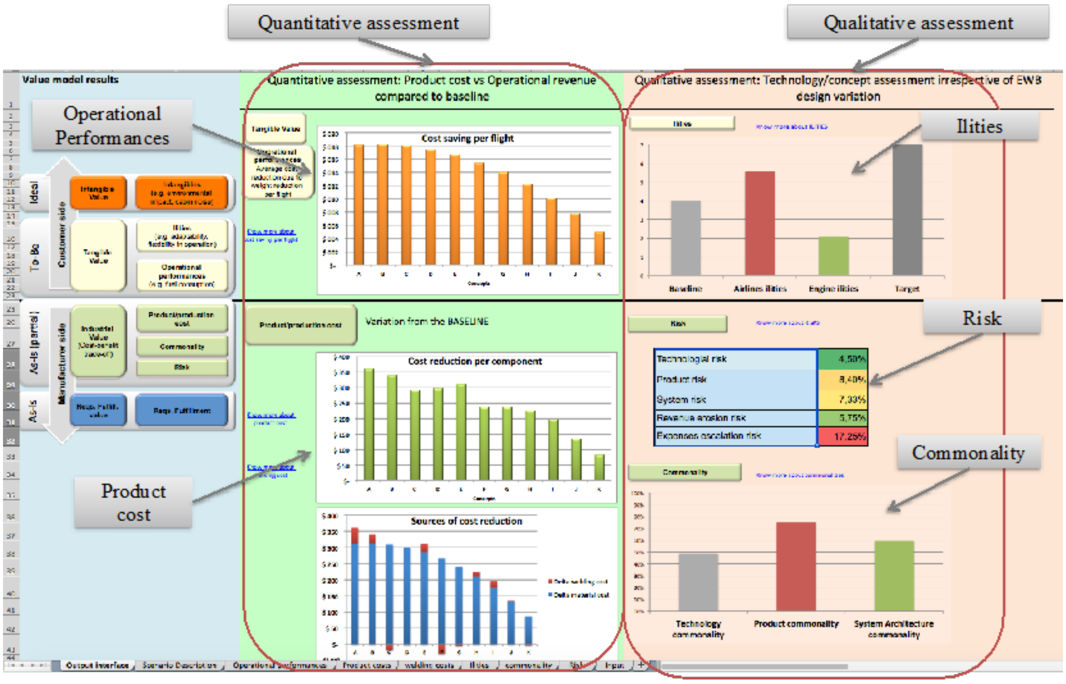

Figure 4. Value model output interface for the analysis of the TRS concept (screenshot)

5 DISCUSSION AND CONCLUSION

This paper has presented a prototype of a value model aiming to support designers in considering a wider stakeholder-oriented perspective in preliminary design. The value model bridges quantitative data from specific engineering simulations with more qualitative and wider value aspects. The prototype targets the preliminary design phases of a product development project, and has his value in enhancing engineers and decision makers awareness of value-oriented aspects that would otherwise be underestimated or neglected, because falling outside the technical horizon and the design practices of the engineers. The value model and its visualization prototype represent one aspects of a wider Value Driven Design methodology. The initial response from users has been positive, and the prototype itself has enabled an organised, yet flexible, dialogue with design teams in the company. Feedback at this stage has already enabled the desired bi-focus on qualitative value aspects with detailed trade studies necessary to support progress in the design team. It is expected that the value model would guide the design teams to the creation of incrementally more complete and mature costs and models along with the maturation of the design.

Given its nature of prototype the model presents a number of limitations and potential improvements. Future work will have the possibility to incrementally improve the model by addressing more in detail the limitation of each value criteria. For instance, operational performances assessment is currently based on weight and fuel reduction using an empirically derived function based on the flight range of a Boeing 737-800. More factors related to engine component design could impact airline operational performances and future work would focus on their identification and mathematical formulation. The function expressing the gallons of fuel saved for one kilogram of weight reduction will be also subjected to further study to verify its generalization, as well as the definition of the "multipliers" of weight reduction. A sensible research effort is nowadays in place to improve the part of the model estimating the product costs. The automatic definition of an operation list with related time and cost information for a concept would allow a more reliable preliminary assessment of the product and process cost.

Ambiguity and uncertainty are always present in the preliminary stage of a design, thus also in the assessment of component value. How to make evident to designers where these uncertainties are higher is also addressed in current research, which is trying to estimate and communicate the degree of maturity of the knowledge available when modelling.

The model is dependent to the availability of early design simulation output on a range of design variations; research is nowadays run to improve the availability of those data (Isaksson et al. 2015). Future research shall also be spent in understanding which is the best and more effective way to visualize the output of the value model currently visualized in an excel file.

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ACKNOWLEDGMENTS

The research leading to these results has received financial support by the Swedish Knowledge and Competence Development Foundation (Stiftelsen för kunskaps- och kompetensutveckling) through the Model Driven Development and Decision Support research profile at Blekinge Institute of Technology.