INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

MODELS FOR VALUE-DRIVEN ENGINEERING DESIGN

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Keywords: [this will be inserted automatically]

1. Introduction and objectives

Nowadays, a trend can be observed towards frontloading engineering design activities with both physical and virtual models [Thomke and Fujimoto 2000]. By exercising such models decision makers can early on understand how future scenarios will evolve, hence taking more rational decisions [Simon 1979, Scott 2000] and reducing the risk for rework later in the process.
Recent research in Systems Engineering (SE) stresses the importance of a specific type of models to frontload conceptual design activities with: the value model. This model type embodies a simple idea: decisions made during design should always add value to the solution space. George Hazelrigg [1988] explains this as: "values tell engineers what you want. Requirements only tell them what you don't want". A value model is then a mechanism to identify the design with the highest value among a set of concurring alternatives that meet the requirements' threshold.
A main justification for introducing value models to complement existing requirements establishment practices is that requirements decomposition activities lead to a progressive opaqueness of the initial intent of a design [Monceaux and Kossmann 2012]. As a result, design solutions might not be able to fully meet customer and stakeholder expectations, even if requirements are met. In a nutshell: while traditional design methods, based on requirements, may facilitate finding a feasible solution, they do nothing to identify the best solution [Soban et al. 2011].
Isaksson et al. [2013] further explain that designing value-added systems means for practitioners to look at design trade-offs from the perspective of how much customers 'value' certain capabilities against each other. During conceptual design value models raise awareness about the vastity of the feasible design space and provide the necessary contextual knowledge to orient trade-off resolution towards value maximization. The effect of applying such models is that of reducing delay and rework in the later design phases caused by the selection of a sub-optimal solution strategy [Isaksson et al. 2013]. By taking more informed decisions about the development of new technologies and products, decision makers may avoid targeting local sub-optimal solutions (which are close to the existing baseline design) just because they show to satisfy the requirements.
Value models can help overcoming current limits in SE, mainly with regards to delay, rework and cost of complex systems development programmes [Collopy and Hollingsworth 2011]. Still, value-driven methodologies are in their infancy and many questions remains unanswered. A major one relates to what lies at the core of the value assessment activity. Several value assessment techniques exist: surplus value models, performance per cost measures, net benefit analysis, real options, Quality Function Deployment (QFD) and others. Still, Soban at al. [2011] in their research agenda pinpoint that a generic process for "choosing the most appropriate form of a value function for a given class of problems" is still lacking, and that it is not clear to what extent "there is such a place for iterative value function updates" as more information becomes available about a particular design. These gaps in the

literature, which are claimed to hinder value-driven design initiatives to gain momentum and becoming widespread [Soban at al. 2011], have suggested the authors to formulate and investigate the following research question:

- How shall value models iteratively translate customer desires into terms that are meaningful for engineering design decision-making?

This paper elaborates on the above and presents an iterative approach for value-driven engineering design that considers the need to update the value model definition as far as new information become available in the process. The paper initially presents four case studies, two in the aerospace and two in the road construction equipment sectors, all related to the application of model-based enablers for value to complement existing SE practices during conceptual design. It then proposes a framework illustrating the different stages in the evolution of the value model during preliminary design. The final section discusses the learning from the cross-case study, and highlights the features of such an iterative approach.

2. Method

The research is shaped on the Design Research Methodology (DRM) proposed by Blessing and Chackrabarti [2009]. Within DRM, the authors adopted a multiple case study approach [Yin 2013]. Data were gathered across different cases both in the aerospace and the road construction industry.

Following the guidelines for qualitative research proposed by Miles et al. [2014], the research question was iteratively developed from the conceptual framework, and guided the sampling plan across cases and the development of the coding scheme. The authors adopted a purposeful sampling strategy, which focuses on selecting information-rich cases whose study is aimed at illuminating the questions under study [Patton 2005]. Data collection activities featured mainly semi-structured interviews, together with regular multi-day physical co-creation workshops and analysis of internal company documentation as triangulation method. Respondents were located mainly using a snowballing technique [Warren 2002]. One respondent was initially located, who fulfil the theoretical criteria. This person helped in locating others through her or his social network. In the selection, both the 'meatiest' cases and the 'peripheries' were considered [Miles et al. 2014]. This means that the sample covers a variety of roles, from managers to CAD engineers, from marketing practitioners to information technology experts.

In the initial phase the interviewing activity can be described as exploratory and largely descriptive. As suggested by Warren [2002], from the initial research question the interviewers developed a set of 10-12 more specific inquiries: those guiding the conversation, those clarifying answers or requesting further examples and those pursuing the implications of answers to the main question. The first cycle of coding [Miles et al. 2014] featured elemental (such as 'descriptive', 'in-vivo' and 'process' coding), affective (mainly evaluation coding) and exploratory methods. Codes emerged progressively during data collection from the provisional 'start-list': this inductive approach helped uncovering local factors in the study. The array of individual codes was revised as field experience grew, and later arranged into patterns. Later in the process interviews became more confirmatory in nature. The authors compiled visual representations and demonstrators of the emerging modelling concepts, which were verified with company stakeholders to identify critical topics for modelling.

Reflective learning was aided by the participation in regular debriefing activities, which have taken the form of regular (bi-weekly) virtual meetings. The findings have also been iteratively discussed and validated with a broader set of industrial practitioners in co-located research workshops.

3. Specifying models for value-driven engineering design: a review

Richardson et al. [2010] well explain the underlying dichotomy of SE, which is that of satisfying requirements on the one end, while making good design decisions on the other end.

Von Neumann and Morgenstern's [2007] theorem of expected utility is a milestone in reconciling these views. Originally published in 1944, it formally kicked-off the discussion about using value as a basis for decisions, and triggered several decades of research aiming at applying these principles in practice. A major contribution in this direction comes from Keeney and Raiffa [1993], who proposed a multi-attribute utility function that combines separate preferences, elicited under uncertainty, for each individual attribute of a design. Hazelrigg [1998] later proposed a Decision-Based Design framework that considers the profit gained by a firm through a system as driver for decisions. In practice, multiple attributes for a design are first drawn into a single system-level attribute, which is then defined as the fundamental driver of value.

More recently, Collopy and Hollingsworth [2011] elaborated on Hazelrigg's framework and proposed a value centric process for the design of complex systems named Value Driven Design (VDD). VDD is explained as a cycle. Firstly, designers attempt a solution in the design space, creating a detailed representation of design variables. Later, they produce a vector of attributes that mirror the customer preferences or 'value scale'. The core of the VDD methodology is the objective function used to assign a score to rank a design. Several examples of application of such function exist in literature, with Net Present Value (NPV) and Surplus Value (SV) being the dominant approaches [Price et al. 2012]. The configuration featuring the highest NPV (or SV) is considered the preferred configuration to date: the design team may accept it as its product, or may try to produce an even better design by going around the cycle again.

Several authors discuss the weaknesses of the VDD optimization loop and its focus on a single monetary value function. Collopy [2012] itself raises concerns about the trustworthiness of such a deterministic model, as it may hinder communication among decision makers. In their VDD agenda, Soban et al. [2011] stress that often a qualitative assessment of the 'goodness' of a design is to be preferred against a numerical (and monetary-based) encoding of preferences. Lee et al. [2014] highlight that an effective value-driven process should not only be repeatable and resembles the decision maker's actual preferences and beliefs, but shall also allow decision makers to customize the refinement of the model until it is sufficiently accurate. Monceaux et al. [2014] further claim that VDD functions are only suitable for detailed design, being too data intensive for the conceptual design phase. Siyam at al. [2015] show that the move towards 'servitization' makes difficult to apply deterministic value assessment approaches, because uncertainty and ambiguity dominate even more the early phases of the design task.

4. Case studies: development of models for value-driven engineering design

The research presented in this paper is based on findings from four different case studies. Two were conducted in collaboration with an aerospace sub-system manufacturer, while the remaining two with a road construction equipment manufacturer. In spite of different business environments, both partners follow SE practices in their development process, and both are challenged with the problem of assessing value-adding capabilities of a design since an early phase, to guide the requirements establishment task. The following sub-sections provide a description of the case studies detailing their peculiarities and the use of value models in the different context.

4.1. Case 1: development of an aero-engine hot structure component

The first case study focused on a design situation where designers needed to take an early stage decision concerning the development of a new high temperature engine component (for a more complete description see Hallstedt et al., [2015]). High temperatures in the engine core meant for the component to be realized using exotic materials and advanced manufacturing techniques. A few of these combinations, while ensuring technical performances, were seen as a potential threat in terms of sustainability impact. Failing to meet sustainability requirements would have had negative effects on the company business: the most severe one concerned the possibility of being black-listed by potential customers, while less severe scenarios pointed to a rapid escalation in production and logistic costs. Early stage value modelling needed then to include sustainability as one of the criteria for design concept selection.

The definition of a vector of attributes and of an objective function, as indicated by the VDD literature, was not considered a suitable way forward for value modelling in this situation. The link between sustainability and value provision was dependent by the evolution of the business scenario (such as the introduction of legislative requirements), which was very uncertain at the time of the analysis. Hence, rather than on the development of an optimization value function, the value assessment activity focused on the development of a qualitative model that was iteratively refined by the results of a quantitative Net Present Value (NPV) calculation generated across a number of possible future scenarios. The scope of the NPV model was more that of making the design team members to converge on the meaning of 'sustainable value' creation, rather than that of a decision making tool. Still, by presenting the results from several scenarios in form of economic assessment, individuals were guided in making assumptions, restraints, and statements explicit. The NPV model was used as common denominator for the different team members to collaborate and share their knowledge in the task. This knowledge, that otherwise would have remained implicit or high-level, was used then to refine the qualitative assessment model and to identify the configuration to be followed up in the detailed design stage.

4.2. Case 2: development a sub-system for large road construction equipment

The second case study relates to the design of a new sub-system for a double drum asphalt roller. Four alternative concepts were generated by the design team on the basis of the customer need list. The team initially defined a 'baseline' concept that mirrored solutions installed on existing machines. A second concept featured an incrementally improved sub-system, very similar to the baseline in terms of its architecture, but different in one key geometrical dimension. A third option embedded a very radical solution, which had significant cascading effects on the entire geometry of the machine. The last alternative featured a design similar to those of the competitors, and different from the baseline design. These four concepts were described by a list of engineering characteristics, which captured the main differences among the 4 solution strategies. Each concept influences the operational behaviour of the machine and other lifecycle aspects. Importantly, it may suggest the roller operator to follow different 'patterns' while performing compaction operations. In turn, it influences a range of key performance indicators for compaction, such as lead-time, quality, fuel consumption, machine availability, maintenance and repair operations, resale value, operator comfort and customer image.

Value modelling activities initially focused on the analysis and prioritization of a list of customer buying criteria, to be later used as metrics to benchmark the 4 options. This step brought to the identification of several criteria from the initial need list, with different levels of granularity. Interviews with engineers, process owners and experts at the company, together with the analysis of internal company documents, reduced them to a sub-set of linearly independent dimensions. These dimensions were further rank weighted to represent the strategies for value creation of different markets, regions and customer types. The four solution options were then benchmarked qualitatively, using the COncept Design Analysis (CODA) method proposed by Eres et al. [2014].

The rank-weighted value dimensions were mapped against the set of engineering characteristics describing the 4 machine designs. The resulting decision matrix featured 231 intersections, which were resolved in 25 strong (9), 24 weak (3) and 30 minimal (1) correlations, plus 151 blank cells. A Relationship Type (maximization, minimization, optimization or avoidance) further detailed the nature of these correlations. Once 'design merit' scores were obtained at each intersection, the total score of a design concept in each value creation strategy was aggregated using rank weights. The information characterizing the intersections in the CODA matrix was used to create a first version of a Total Cost of Ownership (TCO) model for the machine. The analysis aimed at quantifying the economic gains of new design concepts against the baseline design. The main cost drivers considered in the model were derived from the work of Ferrin and Plank [2002]. A Wear and Maintenance model and a Repair model were further created to simulate maintenance and repair costs for the machine, together with downtime cost. The results of these models were fed into the TCO analysis. This enabled engineers and designers to visualize the monetary impact of each design concept on the customer operational process on a 10-year time period.

4.3. Case 3: development of an aero engine turbine rear structure

A third case study focused on the development of a turbine real structure (TRS) for a commercial aircraft engine [Bertoni et al. 2015]. This sub-system is dedicated to transferring different loads and redirecting the aero-engine outgoing airflow. The objective of the research work was to create a value model whose results could be integrated with the output of the early design simulation based on finite elements models. The goal of the case was to find the best way to calculate and visualize the value generated by small design variations of a component, so to automatically run a value assessment routine for a number of possible designs in a short timeframe. A major challenge in the activity concerned the different levels of detail to be managed in the analysis. Small design variations of a TRS part, such as the angle or the thickness of a flange, could have a noticeable influence on the component in term of operational performances and product cost. At the same time more intangible elements, such as risk or commonalty in development, could only be related to the TRS as a whole, and not to one of its specific parts. However not considering intangible aspects in the evaluation would have drastically reduced the usefulness of modelling the value of design alternatives, since the design space would have already been constrained by the current TRS solution. The modelling issue was addressed by the definition of a Value Creation Strategy (VCS) capable of collecting the needs and expectation of different stakeholders, and later by the development of a value model that was not only hybrid in nature (i.e. qualitative and quantitative) but that was also meant to work at two different levels of detail, which is focusing on the component and its parts. The issue with modelling design variations was addressed by developing specific mathematical functions using as input both existing expert knowledge and the output obtained by the computer based simulations (e.g. weight, geometry of the parts). The 'intangible' value of the whole component was instead assessed in qualitative terms, based on expert evaluation. Finally both assessments were visualized in a unique interface to enable the trade-off between different TRS designs and between different minor variations of the same TRS. A prototype of the value modelling approach was developed for validation purpose.

4.4. Case 4: development of a sub-system for small road construction equipment

The fourth case study related to the design of a new generation of small asphalt compactors. Market and customer segmentation activities brought to the identification of a set of criteria (with rank weights) describing preferences in different regions and for different customer company structures. This activity was followed by the construction of an initial Total Cost of Ownership function. In order to refine and populate the latter, the machine was further modelled using Functional Flow Block Diagrams (FFBD) [Blanchard and Fabrycky 1990] and alternative sub-system designs were analysed in terms of how different parts contribute to delivering the required product performance while reducing the overall product cost. The TCO and FFBD descriptions highlighted that the ability to absorb near-field and far-field transmitted noise is an important factor to raise customer value perception, having a major impact on the machine ability to deliver value in operation. Noise absorption was then selected as main topic for the analytical study. The noise from the asphalt compactor was recorded and later imported into the MATLAB® workspace to create a vector description of the sound. The effect of noise absorbing material was then simulated in the MATLAB® environment at varying frequencies. Absorption performances and cost data for the proposed solutions were fed back to the quantitative value model, refining the analysis.

5. A framework for the iterative definition of value models

The case study findings led to the identification of a generic process for iterative value models specification in the SE process. The process is composed of 5 main modelling areas, which are linked to the evolution of the design concept description. Following the structure proposed by Isaksson et al. [2015] for the development of a model based decision support for value and sustainability, these areas are described within the Knowledge Value Stream–Product Value Stream (KVS-PVS) framework proposed by Kennedy et al. [2008]. In Kennedy's model, the innovation process at the company can be divided into two separate value streams. The KVS represents the capture and reuse of knowledge about markets, customers, technologies, products and manufacturing capabilities, which is general across projects and organizations. The PVS is specific for each project and consists of the flow of tasks, people and equipment needed for creating, for example, drawings, bill of materials and manufacturing systems.

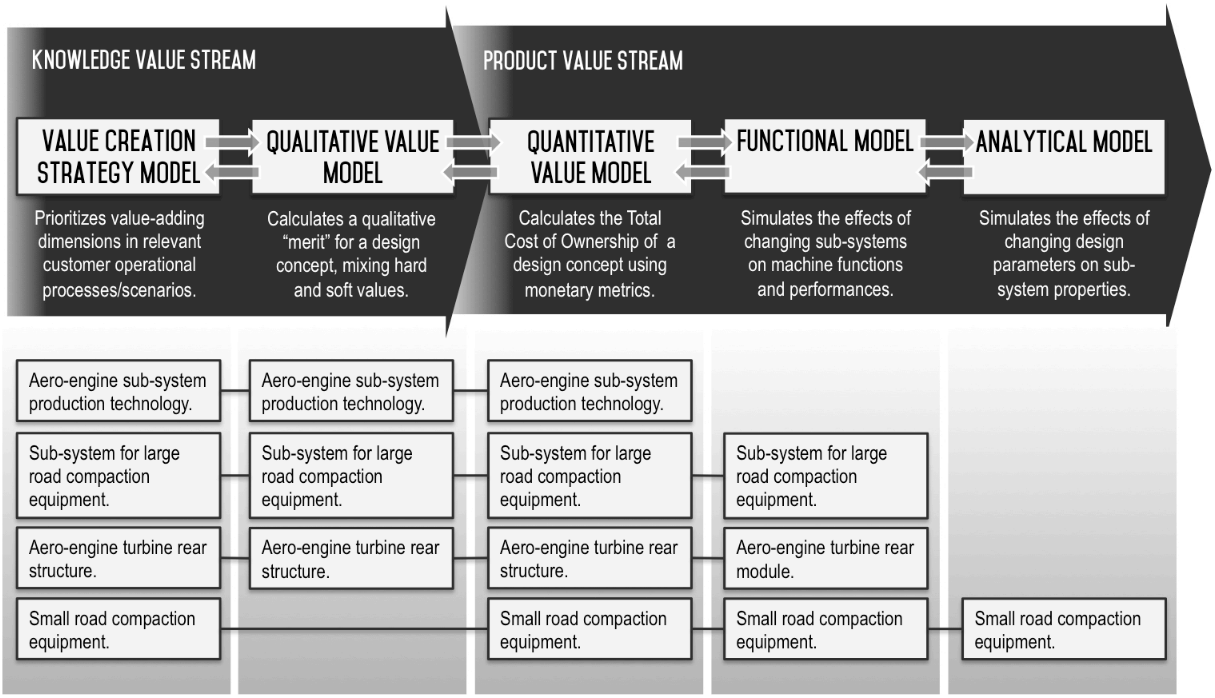

Figure 1: Models for value-driven engineering design with related case studies

The five modelling areas in the KVS-PVS framework represent iterations in the construction of a system value model. This shall be intended as a recursive activity, which goes back and fourth between the two extremes of Figure 1 as far as more information about the design becomes available. The output of a value modelling activity is used as input in the creation of a more detailed and robust model while moving towards the end of the PVS stage. Lessons learned from the models on the right-end side of Figure 1 are fed back to previous models, refining their description and content.

Value modelling activities in the KVS kick-off by capturing the strategy for value creation of customers and stakeholders in the system, and representing them in terms that are meaningful for the cross-functional design teams. This activity aims at picturing what the intent of the design activity is, so to provide a common ground for elaborating on the expected capabilities of a new system. A feasible modelling approach is that of capturing such strategy by distilling a manageable subset of linearly independent 'value' dimensions from the Voice of the Customer and need description. These dimensions, which are initially generic for the system, can be detailed in more specific 'value drivers' for given sub-systems or components. Dimension and drivers are further rank weighted to display which aspects of the solution are emphasised by different markets, customer types and applications. The strategy is iterated and refined as far as new information about market conditions, competitors and expected capabilities becomes available. Rank weighted dimensions and drivers represent a first output of the value-modelling methodology, which is used as input in the next modelling step.

Step 2 foresees the translation of the above strategy into a benchmarking mechanism for comparing solution directions. The role of the models changes from communicating opportunities for value creation to measuring the 'goodness' of early stage design concepts against a given baseline. The study shows a preference towards the use of qualitative models in the assessment. Decision matrices are used to map value dimensions identified in the previous step against a preliminary set of engineering characteristics of a solution. The mapping process is iterative: initial attempts (e.g., the matrices proposed by Pugh [1990]) gradually evolve into more structured representations (e.g., Quality Function Deployment [Collopy 2009]). In order to better capture the rationale behind the assessment, and to document richer lessons learned that can be exploited in future projects, it is possible to further extend QFD and embed more complex relationships in the mapping. When a satisfying combination of characteristics is found, the team must decide whether to invest resources in optimizing such a combination and to communicate this information to the systems integrators (i.e.,

the engineering characteristics become embryo of the system requirements), or to continue working on critical areas of the system that necessitate higher value contribution.
Entering in the PVS stage, life cycle cost models become appealing to raise awareness on the economic impact of alternative design concepts in the customer operational process. These models are iterated as long as the product description evolves, and data may be obtained from increasingly refined functional and analytical models. Still, when quantitative models are approached for the first time, the design space is dominated by information volatility. For this reason, initial quantitative value models insist on a conceptual approach [Gupta 1983], which consists of a set of hypothesized relationships expressed in a qualitative framework. Main cost drivers are derived either from the literature (as happened in the road construction case studies) or from company historical data (as happened in the aerospace industry case studies).
The initial TCO function may later benefit from the results of ad-hoc simulations that compute revenue and cost data for the different phases of the product lifecycle. In the fourth iteration the analysis likens traditional Value Engineering methods [Cooper and Slagmulder 1997]. At this point the purpose of the value modelling activity is to perform a more systematic decomposition of a system so to eliminate or modify anything that causes unnecessary costs, without damaging essential functions. Identifying and breaking down functions allows the representation of interactions between sub-systems and components in a complex product, and helps in cascading down value-adding functions to lower level functionalities, so to identify main areas of improvement.
In the fifth iteration, analytical models are used to perform tradespace studies on alternative design configurations, so to enable optimization of the different parts of the sub-system. Methods such as finite element analysis, computational fluid dynamics or modal analysis are here applied to enable the optimization of a design or of a part of it.

6: Discussion: iterative development of models for value-driven engineering design process

Classical VDD literature emphasizes the role of value models as optimization tools: once the monetary value function is defined, it is iterated with emerging design configurations until the most satisfactory solution is found. The empirical studies show that, more than a mechanics to identify an optimal design, a value model is a tool for progressively learn what a ‘good design’ is. Value models are seen as enablers for learning about the contextual and incidental factors affecting the level of satisfaction (or dissatisfaction) generated by a system along its lifecycle.
The highly concurrent nature of modern SE processes [Prasad 1996] also emphasises the need to learn about how to work in cross-functional and cross-disciplinary teams. Organizations face the problem of facilitating knowledge sharing and coordination in these teams, creating a common shared picture of the ultimate goal of the design activity. In this learning process, the iterative development of the model is a must: value-modelling activities changes throughout the entire conceptual design process to facilitate such learning. Such finding provides an affirmative answer to the question raised in the VDD research agenda [Soban et al., 2011]: the value function does change as far as more information about the system is collected. It evolves from being a description of the problem domain from the point of view of value creation, to describing the value-adding features of alternative system architectures, to eventually highlighting the capabilities vs. cost of sub-systems and parts.
Value models are differently shaped depending on which phase of the conceptual design process the team is in. Being a tool for learning, models follow the increasing awareness of the team. The value model can be seen as a scalable platform, which can be expanded from the simplest definition to the most complex analyses. It plays the role of a shared object around which the discussions about value contribution can be staged. These discussion triggers negotiations, forcing team members to assess their perceptions about the value of a design and to resolve conflicts where conclusions differ. The empirical study shows that value functions as expressed in VDD are not fully effective in this respect, but shall rather expand along two axes. Firstly, they shall provide more contextual information about the underlying rationale of the function and the maturity of the information on which they are built (“i.e., where do the results come from?”). Secondly, they shall suggest a course of actions and

actionable measures (i.e., “what do we do with the results?”) so to render more value in the next iteration.

Working with value models in the KVS

KVS activities aim at defining the scope of the development effort, and focus on the exploration of the potential implications of a broad number of possible technologies. In this ‘scoping’ phase decision support shall enable the screening of candidate solution strategies with limited effort and time, typically in the order of days. Furthermore, it shall enable the design team to handle situations where the information available is scarce, immature and incomplete. This is followed by more detailed analysis aiming at identifying emerging designs.

Decision support shall enable the design team to confine the design space and down select concepts from a range of possibilities. Iterations here shall be executed within a few weeks, and a first set of preliminary system requirements shall be available short after these iterations. In this context, models are needed to synthesize heterogeneous information related to customer needs and desires, as well as to more technical requirements, into metrics that can be used to benchmark solution options.

A crucial role played by the value model at this stage is that of handling and dispatching information outside organizational boundaries, involving all stakeholders (systems integrators, suppliers and subcontractors) in the concurrent development of solutions. Monceaux and Kossmann [2012] have observed that a main issues is SE is related to the lack of mechanisms to concurrently define the scope of a project across the supply chain when detailed contractual requirements are not yet available. Early stage iterations across supply chain levels are needed to explore the problem space and to negotiate the features of solution, before formal requirements are made available by the system integrators. Value models have been earlier proposed to support such a process [Isaksson et al. 2013], and the study further confirms such observation.

The role of the value model becomes that of describing a value-adding strategy for the design of a new system, both with regards to innovative hardware and service solutions, which can be shared between organizational borders before formal requirements are made available. Enabling a more concurrent mode in the definition of the strategy would eventually help in defining more meaningful requirements for the system.

Working with value models in the PVS

The transition from KVS to PVS is characterized by an increased maturity in the way system concepts are described. Increased data availability makes it possible to perform more in-depth value analysis, so to select winning design options to be later followed up in the detailed design stage. Both product-and process definitions exist at this step, and they are refined to minimize risk, cost and any other requirements compliance. Models shall now enable a greater depth of analysis in the given context. The time frame for the usage of decision support tools is still time constrained; yet studies may now expand to several weeks. In this context, quantitative value models are suggested to support the selection of a product concept from the pot of available alternatives.

Operational performances (e.g., use of resources or output quality), operational support (e.g., downtime or maintainability) and ‘ilities’ (e.g.; changeability or scalability as defined by McManus et al. [2007]) are the most immediate metrics at this stage, because they are the ones most directly influencing customers’ purchasing behaviour. At the same time, value models shall enable design teams to mix system performances with more intangible aspects, such as brand acknowledgement, charm factor or easiness to use. One additional level of analysis relates to assessing how the system will behave in accordance (or in conflict) with competitive products, as well with product complementing or substituting the offer. In this picture, value models shall aim at capturing the dynamic of value creation, and the evolution of value scales in the foreseeable future. Evolution in normative regulations, societal trends and sustainability awareness are examples of aspects that are difficult to systematically represent in the requirement description. Value models are therefore expected to cover such gap, capturing and summarizing such heterogeneous aspects in a unique metrics for down selecting product alternatives and identifying an optimal design.

Conclusions

The paper has discussed the role of value models in the engineering design process with regards to the questions posed by the VDD research agenda [Soban et al., 2011]. It shows that the iterative development of a value function is a 'must' when its objective is that of (1) working as a learning mechanism, (2) serving as a platform to capture the 'intangible value' of a system, (3) playing the role of boundary object with the cross-functional team, (4) raising concurrent engineering practices across the supply chain, and (5) communicating rationale and uncertainty in the design task.

As a result, the paper presents a framework for the iterative development of value models in conceptual engineering design. The framework is derived from findings related to four case studies, and it is composed by five iterative stages within the KVS-PVS innovation project framework proposed by Kennedy et al. [2008]. The framework describes how the iterative development of value models shall encompass qualitative dimensions in early stages, and how it shall move toward more quantitative assessments when information becomes available and the level of detail in the system description increases.

This result may be considered a step forward towards a larger research effort whose purpose is to create a model-driven platform for value-based decisions in conceptual design. The purpose is to use models to capture and represent 'value' aspects, and link these to the engineering design process. The models used in the presented case studies have been exercised in different industrial domains; still they are comparably low-fidelity and simplistic. Future research shall aim at applying them in more data-rich situations and at integrating them with other tools, in order, for instance, to improve the visualization of modelling results.

An interesting future research track is related to the use of Data Mining techniques to support decision makers in populating the value models [Isaksson et al. 2015]. Nowadays technology makes it possible to continuously log data from a system during its entire lifecycle, and to apply data mining algorithms to discover patterns and make predictions. An interesting aspect is related to the ability of organizing such patterns to reveal the structure of the decision to be made, building structures (e.g. decision trees) to populate (or complement) value models.

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.

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