EVOKE: A VALUE-DRIVEN CONCEPT SELECTION METHOD FOR EARLY SYSTEM DESIGN

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Abstract

The development of new technologically advanced products requires the contribution from a range of skills and disciplines, which are often difficult to find within a single company or organization. Requirements establishment practices in Systems Engineering (SE), while ensuring coordination of activities and tasks across the supply network, fall short when it comes to facilitate knowledge sharing and negotiation during early system design. Empirical observations show that when system-level requirements are not available or not mature enough, engineers dealing with the development of long lead-time sub-systems tend to target local optima, rather than opening up the design space. This phenomenon causes design teams to generate solutions that do not embody the best possible configuration for the overall system. The aim of this paper is to show how methodologies for value-driven design may address this issue, facilitating early stage design iterations and the resolution of early stage design trade-offs. The paper describes how such methodologies may help gathering and dispatching relevant knowledge about the ‘design intent’ of a system to the cross-functional engineering teams, so to facilitate a more concurrent process for requirement elicitation in SE. The paper also describes EVOKE (Early Value Oriented design exploration with KnowledgeE maturity), a concept selection method that allows benchmarking design options at sub-system level on the base of value-related information communicated by the system integrators. The use of EVOKE is exemplified in an industrial case study related to the design of an aero-engine component. EVOKE’s ability to raise awareness on the value contribution of early stage design concepts in the SE process has been further verified with industrial practitioners in ad-hoc design episodes.

Keywords: Requirements elicitation, concept selection, systems engineering, value-driven design, decision-making, knowledge maturity

1. Introduction

Typical approaches for requirements elicitation (e.g., Geisser and Hildenbrand 2006, Pohl 2010) begin with the assumption that the Systems Engineering (SE) (INCOSE 2011) process shall only deal with the step-by-step transformation of the customer needs into specifications of a design (Durugbo et al. 2013). This view is challenged by the reality of the industrial landscape in the domain of technologically advanced products. In the aerospace sector, for instance, Original Equipment Manufacturers (OEMs) are increasingly building strategic alliances with customers, research centers, subcontractors and even competitors (e.g., the International Aero Engines consortium, <http://i-a-e.com>), to acquire the range of skills, knowledge and expertise needed to develop new products, services, or combinations of them (Acha et al. 2004, Tien 2012).

Research in SE shows that, in such a consortium, requirements elicitation is far from being a linear, monolithic process; rather, it follows a more concurrent process (Prasad 1999). In order to improve clarity, awareness and understanding of what should be included in a system design, and hence to minimize development time and later rework, iteration and negotiation with customers and stakeholders must be established since the earliest design phases (Jiao 2006, Withanage et al. 2010). Information about where user needs originate and mature becomes critical to understand which sub-system performances have to be sacrificed to optimize the overall system behavior. This makes systems engineers to go back and refer to the original construct of ‘value’ to orient their early

stage design decisions (Monceaux and Kossmann 2012).

However, when moving from the macro level to the micro, this ‘value’ notion becomes blurrier, and contextual understanding gets lost when requirements are communicated down the supply network (Monceaux et al. 2014). Lacking of a ‘sound basis’ for decision-making, engineers working at sub-system and component level tend to avoid opening up the design space. They rather follow their ‘normal specifications’, targeting conservative solutions that are potentially less prone to corrective rework and unplanned costs (Isaksson et al. 2013). These ‘local optima’ seldom embody the best possible result for the overall system. Most likely they hinder the possibility of identifying solutions that would work even better and that maximize value (Collopy and Hollingsworth 2011). For this reason, value modeling activities become appealing to elaborate an overarching and cross-system specification list that clarifies, early on, the context and underlying intent of the requirements shared by the OEM.

2. Objectives and Method

The paper investigates how value-driven design methodologies can support a more concurrent process for requirements elicitation in complex supply networks. It describes the use of value modeling as an information-driven approach, rather than an optimization methodology, to enable more frequent design iterations across all layers of such networks since the earliest stages of the system design process. The objective is to further illustrate how methods and tools for value-driven design can leverage cross-functional team awareness of the value

contribution of alternative sub-system concepts. As main result, the paper presents EVOKE (Early Value Oriented design exploration with Knowledge maturity), a concept selection method which aims to support systems engineers in:

- ✧ relating the value information at a system-, or even ‘use of system’- level, to the existing sub-system description,
- ✧ benchmarking alternative sub-system solutions concepts using ‘value’ as a metrics, and
- ✧ conducting rapid WHAT-IF simulations of alternative scenarios, where different strategies for value creation are considered.

EVOKE was conceived within the EU FP7 CRESCENDO (<http://www.crescendo-fp7.eu>) project. It was later refined within a Swedish government funded research profile in ‘Model Driven Development and Decision Support’ and within a Virtual Turbine Module Demonstrator initiative financed by the Swedish innovation agency VINNOVA. Action research (Avison et al. 1999) best describes how research was conducted in both environments. Empirical data were collected between May 2009 and April 2016 via interviews, physical workshops and virtual work-meetings with a major aero-engine components manufacturer in Sweden. The findings were iteratively discussed and validated with project partners (aircraft, engine and sub-system manufacturers, universities, research centers and software vendors), which actively participated with their knowledge and expertise to the development of the methodology. EVOKE was demonstrated in a case study related to the development of a major structural aero-engine

component. Verification activities initially concerned the sensitivity of the different parts of the method. In a later stage, they focused on gathering both qualitative and quantitative feedback from the application of EVOKE in design sessions involving industrial practitioners.

3. Value vs. Requirements Elicitation in System Design

Requirements are ubiquitously considered the main decision-making construct for any complex engineering project activity. However, recent literature points out that, for an engineering system, a requirements-centered decision-making process is often unable to assure optimal decisions at an overarching level (Chen et al. 2013) and to eventually add value to the solution space (Collopy and Hollingsworth 2011). The latter is particularly important in the domain of SE, because, as stated by Browning (2003), *“process improvements in product development cannot just focus on waste, time, or cost reduction, but the purpose should be to maximize the product value”*. Accordingly, decisions made during design should always add value to the solution space, because *“it is value that tells engineers what the customers want”* (Hazelrigg 1998). Methodologies for value-driven design aims to cope with this issue, by turning ‘value’ into a driver for the system design activity, as opposed to requirements and/or cost-related characteristics.

Literature shows a great amount of contribution on clarifying (1) what values are defined, (2) who quantify the values and (3) how to justify whether a design responds to these values. Miles (1972) is among the firsts to introduce the value analysis concept. A product

or service is generally considered to have good value if it shows appropriate performances associated with a low cost. Bad value is associated to systems failing to meet performance targets while having a high cost. In this definition, value is considered as a functional attribute of the product, which can be increased either by improving product functions or reducing resource consumption.

During the early 2000's, a significant amount of research on value-centered methodologies was produced at the Engineering Systems Division of the Massachusetts Institute of Technology. Within this group, Olivier de Weck et al. (2003) developed new methods for exploring a design tradespace using Generalized Information Network Analysis. Similarly, Ross et al. (2004) and McManus et al. (2007) considered customer value embedded in the customer process context and proposed the concept of 'ilities' to evaluate the system robustness under changing process conditions. Both de Weck et al. (2003) and Ross et al. (2004) employed a graphic form of optimization, called Tradespace exploration, in which designs are plotted against two orthogonal axes, utility and cost, to measure components of value by their position. The Epoch framework later proposed by Ross and Rhodes (2008) allows the systematic creation of trade-space model(s) to quantify a range of 'ilities', such as survivability, adaptability, flexibility, scalability, versatility, modifiability and robustness. Other methodologies did exist previously, such as Real options for flexibility (Saleh et al. 2003) but just for a few of these aforementioned criteria. Later, Brown et al. (2009) developed a Value-Centric Design Methodology (VCDM), which emphasizes the value of flexibility and robustness.

Value Driven Design (VDD)(Collopy and Hollingsworth 2011) is another major value centric process for the design of complex systems. VDD aims at moving the target of the modeling activity: from identifying a favorite performance point to creating a space where there can be a discussion of product performances, trade-off benefits and drawbacks of different solutions (Dahlgren, 2006). The VDD process is explained as a cycle. Firstly, designers pick a point in the design space at which to attempt a solution. Then, they create an outline of the design, which is elaborated into a detailed representation of design variables. Later, they produce a second description, in form of a vector of attributes that mirrors the customer preferences or 'value scale'. This vector is assessed against an objective function to assign a score to rank a design (Fanthorpe et al. 2011). Engineers can accept such design configuration as their solution, or may try to produce an even better one by going around the cycle again.

The notion of value is also connected with that of 'uncertainty'. In this field, Briceno and Mavris (2005) proposed a method to determine the value of a design under market uncertainties by the use of game theory and net present value NPV evaluation. Cardin et al. (2007) elaborated on uncertainty, using Monte Carlo simulations and financial functions such as Return on Assets (ROA), NPV or Value At Risk and Gain (VARG) to help designers and managers in incorporating flexibility at an early design stage. Schindler et al. (2007) proposed a similar methodology called Systemics for Complex Organizational Systems' Design (SCOS'D), which focuses on the integration of different aspect of stakeholders' demands, such as sustainable development,

environmental issues, safety, hygiene, ethics or working conditions.

3.1 Prominent Valuation Methods for Value-Driven Design

Ross et al. (2010) summarize prominent valuation methods for value-driven design. Each of them attempts to quantify the value of an engineering system, and have a unique interpretation, quantification, and representation of the term value.

Net Present Value (NPV) and Surplus Value (SV) are popular value modeling approaches in SE (see: Castagne et al. 2009, Curran et al. 2010, Cheung et al. 2012, Price et al. 2012). Together with Cost-Benefit Analysis (CBA) (Sassone and Schaffer 1978), they aim at quantifying the discounted cash flows generated by an asset over time, thereby predicting the profit of investing on a given system design.

Multi-Attribute Utility Theory (MAUT) (see: Ross et al. 2004) utilizes a multiple attribute utility curve to output a ranked ordering of system design alternatives. This curve is derived through a set of probabilistic lotteries (scenarios) based on system attributes, rather than on a value function, to allow for the aggregation of monetary and non-monetary stakeholder perceived value of a given system. Cumulative Prospect Theory (CPT) (Tversky and Kahneman 1992) complements MAUT by encompassing decision-making under uncertainty.

Analytic Hierarchy Process (AHP) (Saaty 1980) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Lin et al. 2008) are valuation methods based on the systematic decomposition of a system design into a hierarchy of desirable attributes, which

aggregate to an overarching goal. AHP and TOPSIS are typically represented using decision trees or matrixes. System attributes are pairwise compared by the use of a simple algorithm within each node, or within each cell in the matrix. While AHP is similar to NPV and CBA in its mapping alternatives to a cardinal scale, TOPSIS is identical to MAUT in its output (Ross et al. 2010).

Another method for guiding an engineering discussion about needs and wants of customers is the Pugh method (Frey et al., 2009). Its objective is to compare design options by benchmarking a number of customized criteria, providing a qualitative ranking of the alternatives. Increased resolution in the product description opens up room for more sophisticated approaches such as Quality Function Deployment (QFD) (Akao and Mizuno 1994), which was early on identified as a prominent Value Driven Design model candidate (Collopy 2009). In QFD, aspects of a design, design alternatives, or even potential technologies are scored on how they contribute to each criteria. These qualitative scores are then mapped onto quantitative ones to determine the most value adding solution among a set of alternatives. Value analysis matrixes are also popular in product development literature (see: Wright 1998, p.179) to quantify the component/function relationship in form of monetary units of cost. However, they are mostly concerned with the application of value improvement techniques, and do not address the concept design phase where the problem is more open (Wright 1998).

3.1 Limitations of Existing Valuation Methods in Early System Design

Collopy (2009) summarizes three main desirable features in the course of developing and choosing value models: ‘repeatability’ (results shall not change given identical input data), ‘transparency’ (engineers shall clearly understand why the model behaves like it does) and ‘differentiability’. Importantly, literature agrees on ‘accuracy’ being a less desirable characteristic. Ross et al. (2004) highlight that the role of value models is that of providing consistent and consensus-building tool for making educated (and value-driven) decisions about system design, and not that of providing absolute measures of value. Collopy (2009) further claims that engineering predictive models are somewhat different from value models, because the latter cannot be calibrated. Rather, the pragmatic standard of correctness should be whether the value model is able to rank alternatives in the order of preference. Once a value model is sufficiently precise to meet this standard, there is *“nothing to be gained, and a good deal to lose, by adding more features, detail, or complexity”* (Collopy 2009, p.16).

The analysis of the described valuation methods under the lenses of ‘repeatability’, ‘transparency’ and ‘consensus building’ exposes two main shortcomings with regards to their application for early stage system design, which are:

1. the use of deterministic models for value assessment;
2. the use of quantitative and monetary value metrics.

With regards to (1) the use of deterministic models is found to be of little meaning in early

design (Ullman 1992). Within the VDD community, several claim that such models limit communication among the decision makers and negatively affect early design decision-making activities (Collopy 2012). Several authors (e.g. Soban et al. 2011) support the hypothesis that a qualitative assessment of the ‘goodness’ of a design is preferable against a monetary-based encoding of preference when qualitative data, assumptions and forecasts prevail. Isaksson et al. (2013) further observe that exact quantitative functions are typically missing when performing a preliminary screening of new product technologies. Even if available, they are unlikely to be shared when consortium partners work in a mode of coopetition (Brandenburger and Nalebuff, 1997). This eventually suggests practitioners to look at different constructs to share information about the intent of a design and to overcome Intellectual Property Rights (IPR) barriers (Lindquist et al. 2008). Monceaux et al. (2014) conclude that, while deterministic models for value are relevant in the detailed design phase of a new system, in a conceptual phase different constructs are needed to establish the necessary links between system attributes and the overall ‘value’ of the system.

With regards to (2), several authors notice that value provision objectives often are of less tangible nature than performance or cost targets (see: Woodruff and Gardial 1996). This phenomenon is emphasized by recent ‘servitization’ initiatives in the manufacturing sector (Baines et al. 2009). Shifting the focus from selling a product to ‘providing a function’ highlights the importance of modeling the subjective customer value perception when interacting with a service. In this context, the

application of quantitative and monetary value metrics becomes even more challenging: intangible aspects cannot be captured in the value model by merely using dollars or euros as units of measure (Sakao and Shimomura 2007, Siyam et al. 2015). Experiential (Norman 1988), Emotional (Desmet et al. 2001) and Intangible (Daum 2003) aspects play an important role in the perception of value for such ‘functional’ products. These are often translated into brand name, charm, social status, perceived quality (Zeithaml 1988), or sustainability impact (Hallstedt et al. 2015). While some authors claim that value-driven methodologies are prepared to deal with more intangible value aspects (Price et al. 2012), little evidence is found in literature, with most of the empirical studies focusing on economic aspects (Eres et al. 2014).

4. Value-driven Design Enablers for Early System Design: the EVOKE Method

4.1 Conceptualizing an Information Driven Approach for Early System Design

The empirical study highlighted two main

needs for early stage system design. Suppliers and sub-contractors need access to system-level information as early as possible in the process, to guide the development of technologies with value in focus. Also, multi-disciplinary and cross-organizational design teams require a working environment that supports open dialogue on problems and solutions. These considerations brought to the development of a value-driven design process that links high-level customer expectations to product features at sub-system level, and that communicates back to the system integrator the results of specific value analysis (Isaksson et al. 2013). In this view, value-driven design becomes an information-driven approach that supports early stage decision making in SE: it fosters knowledge exchange among individuals and teams, so that agreement on early system features can be achieved earlier than with optimization-based practices. Figure 1 exemplifies this approach within a simplified aeronautical supply chain, which features an aircraft OEM, an aero-engine OEM and a sub-system supplier.

Figure 1 Value-driven design methodology as information-driven approach (Isaksson et al. 2013).

The approach follows a series of linked activities, with the intent of supporting each manufacturer in reaching a more advanced stage in sub-systems development, compared to what happens when only requirements are made available. The first step deals with capturing and validating stakeholders' expectations across the aircraft and aero-engine manufacturer. Expectations are interpreted and translated into needs, which are rank-weighted on the basis of their importance for a given market context. This joint activity outputs a first version of the so-called *Value Creation Strategy* (VCS). The VCS is the entity (or document) enabling the sharing of early stage design information among the parties in the consortium. It contains a context description, a list of rank-weighted customer needs and a list of suggested Value Drivers (VDs). VDs are system characteristics that are less formalized and more volatile than requirements, and that carry contextual information on solution

directions influencing the customer and end user value perception. VDs are not attached to a target value or function; rather they are overarching descriptions of product capabilities that fulfill the original system needs. A need can be dissembled into many VDs; at the same time, it can have an impact on one or more needs. VDs satisfy the independence condition (Zhang et al., 2013) and are customized for each development, balancing stakeholders' needs and company objectives.

Value-modeling activities are further conducted on the basis of the VCS information received by the OEM. Design options are benchmarked at sub-system level using value models, to highlight an optimum selection of Engineering Characteristics (ECs) with target values that are communicated back to the system integrators. Given this input, a second version of the VCS can be developed: it contains a refined description of the context and of the VDs for the study. This loop increases confidence that the

business case is sound, and that the proposed solutions are achievable. After several iterations, validated requirements are established on the base of the ECs description, and included in the VCS. Importantly, definitions for ‘expectations’, ‘needs’, ‘value dimensions’, ‘Value Drivers’ and ‘VCS’ are standardized by the MoSSEC initiative (<http://www.asd-sgg.org/mossec>).

4.2 Concept Selection in the Value-driven Design Loop: the EVOKE Method

Once VCS loops are initiated, engineers are left with the problem of choosing the most suitable value modeling approach to benchmark design concepts and support decision-making at each stage. EVOKE (Early Value Oriented design exploration with KnowledgeE maturity) is a concept scoring method - in the definition of Ulrich and Eppinger (2008, p.134) - that

translates the VCS information shared by the OEM into meaningful sub-system value drivers. These sub-system VDs are then used to calculate a ‘merit score’ for alternative design options, so to identify the most value adding solution candidate to be communicated back to the system integrator. The EVOKE method for concept selection features the use of three matrices (Figure 2), namely:

- ✧ a *Weighting Matrix*, which cascades down the system-level VCS to the sub-system VDs;
- ✧ an *Input Matrix*, which gathers information about the characteristics of each design alternative under consideration;
- ✧ a *Customer Oriented Design Analysis (CODA) matrix*, which produces a merit score for each design.

Figure 2 The EVOKE process steps within a simplified aeronautical supply chain.

The EVOKE process steps map against the SIMILAR process description proposed by Bahill and Gissing (1998). SIMILAR is used as main reference by the International Council on Systems Engineering (INCOSE) to describe Systems Engineering tasks (see: <http://www.incose.org/AboutSE/WhatIsSE>). The acronym stands for ‘*State the problem, Investigate alternatives, Model the system, Integrate, Launch the system, Assess performance, and Re-evaluate*’ and represents an abstraction of heterogeneous instantiations of the SE processes from different fields. Within

SIMILAR, the *Investigate Alternatives* task deals with the evaluation of alternative designs, exploiting multicriteria decision-aiding techniques to reveal preferred system concepts. At this stage Bahill and Gissing (1998) propose the *System Design Process (SDP)*, a parallel and iterative process for preliminary stages where system requirements and system functions are recursively examined to identify the best possible design. EVOKE activities and matrixes are inspired and map against SDP activities of as shown in Figure 3.

Figure 3 Evoke process steps mapped against the SIMILAR ‘System Design Process’ (Bahill and Gissing 1998).

4.3 Weighting Matrix

The *Weighting Matrix* works as a mechanism to generate a set of *normalized weights* for the sub-system VDs from the engine VCS description. These weights are conceptually identical to those used in traditional concept scoring matrixes (Ulrich and Eppinger 2008, p.134). The *Weighting Matrix* is built on classical QFD and uses strong, weak or minimal correlations coefficients (0,9-0,3-0,1-0) to map

value drivers at engine level with value drivers at component level. Coefficients are summed along each sub-system VD, to obtain a sum of correlations. The sum is weighted against the sums for all the other VDs. The resulting rank weight is later used in the CODA matrix to obtain the design merit score for a design concept.

Importantly, different VCSs, which emphasize different engine VDs, produce different rank-weights for the sub-system VDs. A major benefit of the *Weighting Matrix* is related

to the opportunity of testing the sensitivity and robustness (at varying VCS) of the results obtained at the end of the process. The empirical study highlighted this as a critical aspect in the development of value-driven design enablers for early system design. Given the high volatility of the VCS information in the initial iterations, it is important for sub-system manufacturers to be able to simulate a number of strategies to identify value-robust options. Quick WHAT-IF simulations are run in the matrix by altering the rank-weights in the VCS description. Hence, different sub-system VDs are emphasized, which, in turn, influences the combination of system ECs that is considered optimal for the strategy provided.

4.4 Input Matrix

An important observation from the empirical study is that new sub-system designs are seldom radically new concepts, but rather improvements of already known product platforms. For the engineering team, working with platforms means that the overall function structure of the targeted sub-system is already known, and that variants can be progressively specified from this description. Following the definition given by Pahl and Beitz (1996, p161), platform variants can be therefore considered ‘working principles’, which are concretizations of more generic ‘working structures’. A ‘working principle’ is described by geometrical and material characteristics of a design, and reflects the physical effect needed for the fulfillment of a given function (Pahl and Beitz 1996, p161).

Early in the system design process, the aim of the valuation activity becomes that of assessing the feasibility of alternative platform variants

against the VCS communicated by the system integrators. In the EVOKE method, the parameters used to describe these variants are named ECs. The *Input Matrix* is the entity collecting all relevant ECs for a design. Importantly, while VDs are dimensionless and look at the problem domain, ECs feature a unit of measure and describe a solution direction.

The empirical study further showed a preference towards understanding how such platform variants are positioned against relevant benchmarks, rather than towards producing an absolute value score. For this reason, the creation of the *Input Matrix* is triggered by the description of an existing product *baseline*. From such *baseline*, relevant ECs are selected to describe the differentiating characteristics between such baseline and the innovative designs. Upper and lower boundaries are also specified for each EC. This task stimulates the cross-functional team in discussing the limits of a given product platform, and in agreeing on those baseline features from which technically feasible variants are generated and described. At the same time, these limits ensure mathematical consistency of the CODA matrix functions.

4.5 CODA Matrix

The CODA matrix is at the core of the EVOKE method: by supporting the mapping between sub-system VDs and ECs, it highlights the value adding capabilities of each design option, and supports the cross-functional team in down-selecting value-adding concepts. Given the limits related to the application of deterministic monetary models, as explained in the literature review section, QFD was early on identified as a strong candidate to perform such mapping,

mainly because of its reported transparency in mapping engineering parameters to customer needs (Collopy 2009, Al-Ashaab et al. 2013).

The empirical study revealed limitations with QFD mathematics, which suggested investigating alternative approaches. A major difficulty arises from the different assumptions about the relationship between VDs and ECs. While QFD implies a linear relationship between customer satisfaction (i.e., a VD) and a product property (i.e., an EC), such relationship is most likely to follow a Kano logic and to exhibit a non-linear pattern (Tan and Shen 2000, Sireli et al 2007). QFD struggles to realistically model non-linear phenomena (Erginel 2010, Zhang et al. 2015), and the use of artificial neural networks to model non-linearity (e.g., Tong et al., 2004) contrasts with the ‘repeatability’ and ‘transparency’ principles. This is because artificial neural networks require a large amount of precise and objective information about problem and possible solutions (Kwong et al., 2007), which are not typically available in early system design (Rosenman 1993).

An alternative approach to deal with non-linearity, while maintaining a higher degree of transparency in the process, is to replace QFD linear numeric relationships with non-linear functions (Zhang et al. 2014). The latter borrow the concept of ‘Loss Function’ proposed by Taguchi et al. (1989), and translate it in the House of Quality. The Concept Design Analysis (CODA) (Woolley et al., 2001) is one of the methods that

embed this logic. CODA was eventually chosen to realize the VDs vs. ECs mapping in EVOKE.

In CODA, as in mainstream QFD (see: Ullman 1992 p.121, Rozenburg and Eekels 1995 p.175), VDs and ECs are linked by numeric values (in QFD: 9-3-1-0) to express strong, weak, minimal or no correlation between them. CODA further adds minimization (Min), maximization (Max), optimization (Opt), and avoidance (Avo) type functions to compute a score representing the ‘merit’ of a design.

As shown in Figure 4, Min and Max functions are shaped along an exponential curve, which is considered a reasonable approximation of customer response to changes in a product attribute. In mathematical terms, Max functions describe the increase in customer satisfaction when increasing the value of an EC (p). This value equals 0 as far as $p=0$, and it asymptotically gets closer to 1 as far as p increases. The neutral point η , which expresses the value of p by which customer satisfaction equals to 1/2, determines the slope of the function. Min functions work in a similar manner, but with an opposite logic, going from a design merit of 1 to a design merit asymptotic to zero as far as the value of p increases. The shape of Opt and Avo functions mirrors that of a Gaussian distribution anchored on a preferred target value. This value indicates a customer satisfaction of 1 in the first case, and of 0 in the second case. Their shape is further regulated by a so-called tolerance point (τ), which works in a similar way as the neutral point η .

Figure 4 Definition of non-linear functions in the CODA approach (Khamuknin et al. 2015)

By varying neutral and optimum points it is possible to draw different customer responses to changing product attributes: an ideal design solution shall obtain 100% design merit score at each EC/VD intersection. However, most of the time, maximizing an engineering characteristic increases the design merit only for a set of value drivers, while decreasing others. Hence, the engineering team's task is about finding the right trade-offs to optimize the ECs toward the best possible value score (Eres et al. 2014), within the domain of feasible platform variants.

The empirical study revealed further preferences with regards to supporting early stage decision-making, which suggested the authors to

extend CODA with the concepts of *Target merit value* and *Knowledge Maturity*.

The notion of *Target merit value* expresses the desirable outcome of the design task. Such target can reflect a vision emerging from long-term forecasts, or can be calculated, for instance, as 110% of the *baseline* value score. If the *Target* is met, the design is considered to be satisfactory. If not, ECs have to be fine-tuned to trade excellent capabilities in some areas (i.e., in relation to a set of VDs) and deficiencies in others.

The concept of Knowledge Maturity (KM) (in the form proposed by Johansson et al., 2011) is used to indicate how much the engineering team can trust the material entering in the value

assessment activity. Computing the KM of a system design concept aims at assisting decision makers in achieving a better understanding of what uncertainty in the design task involves. KM is used in the CODA Matrix to assess the maturity of correlations, functions, neutral/optimum points and tolerances: these may reflect mathematical formulas or experimental evidence (high KM), or might be the result of educated guesses (low KM).

Information about the winning option (which is, the list of ECs describing the most value-adding design) is eventually fed back to the system integrator. The process is iterated in the next evaluation stage, likely with increased system resolution and better differentiation among design concepts.

5. Case Study: Aero-Engine Intermediate Compressor Case

The aerospace sector provided a favorable environment for the development and experimentation of the EVOKE method, for two main reasons. It features complex products made of many interfacing sub-systems and components, which are designed by a plethora of individuals from a large variety of suppliers and sub-contractors.

Furthermore, aerospace companies are becoming similar to automakers in the way they deal with customer value. Even if operational cost is still the main success factor for a new aircraft development program, dimensions such as comfort, timeliness, entertainment and environmental consciousness are becoming critical to attract passengers and airlines.

EVOKE was prototyped and demonstrated in a case study related to the development of an

aero-engine intermediate compressor case (IMC). The IMC is the biggest static component of an aero engine, and its main functions are to support surrounding parts, keep the airflows separated, off-take bleed air and transfer the thrust from the engine to the airframe.

5.1 EVOKE Weighting Matrix

The VCS communicated by the system integrator (i.e., the engine manufacturer) featured seven main ‘needs’, each one characterized by a varying rank-weight expressed in percentage.

For simplicity purpose, each need was synthesized in form of a ‘value dimension’, expressing the need statement in a less verbose form. These dimensions were: *Emissions Levels*, *Specific Fuel Consumption*, *Noise Level*, *Operational Reliability*, *Bleed Air Quality*, *Direct Operating Costs* and *Electrical Power Output*. Each need was detailed in terms of engine value drivers.

The latter were mapped against the specific VDs for the IMC, which were collaboratively defined by the design team and the researchers. The number of relevant sub-system VDs was limited to a total of 10, mainly because literature in decision-making suggests this to be a good trade-off between simplicity and detail in concept selection activities (see Zanakis et al. 1998).

Sub-system VDs represent directions of investigations for the design of the new sub-system: they can be pictured as dimensionless macro-categories or requirements indicating ‘topics’ that shall be prioritized in early systems design. The sub-system VDs chosen for the IMC were:

- ✧ TEMPERATURE, PRESSURE, WEIGHT and DRAG, which point to the performances of

the propulsion system;

- ✧ RELIABILITY, AVAILABILITY, ADAPTABILITY, MANUFACTURABILITY and WELDABILITY, which capture aspects related to the operational phases of the hardware, and of supporting services, along the IMC lifecycle;

- ✧ KNOWLEDGE REUSE, which expresses the ability of reusing results or expertise from other projects, and represents an indirect measure for risk.

Figure 5 shows an extract of the *Weighting matrix* for DRAG.

Figure 5 Extract from the IMC Weighting matrix

Correlation coefficients (0,9-0,3-0,1-0) are assigned at each intersection between DRAG and the engine VDs (for instance, ‘Volatile Organic’). The sum of correlation coefficients for all the intersections related to the *Emission Levels* value dimension renders a score of 4,5 (the result of: $4 \times 0,9 + 3 \times 0,3$). This sum is weighted against the sum of coefficients for the other sub-system VDs along the same need, rendering a rank weight for DRAG (in the example: 13,54%). By multiplying the latter by the engine value dimension weight (in the example: 15,14%), and repeating the process for all value dimensions in the VCS, it is possible to obtain the overall impact coefficient for DRAG (14,75%) to be later used in the *CODA*

matrix.

The *Weighting Matrix* can be used to test the robustness of the value analysis by altering the rank-weights in the VCS description, so to simulate alternative strategies for value creation in the design of the system (Figure 6). For instance, in some projects the system integrators might want to generate value for their customers by emphasizing performances in operation. This means maximizing ‘value dimensions’ such as *Specific Fuel Consumption*, *Direct Operating Cost* and *Emission levels*. The *Weighting Matrix* reveals that this strategy emphasizes TEMPERATURE, MANUFACTURABILITY and PRESSURE VDs for the IMC component (Figure

6). In other situations, they might rather consider adopting a different VCS. Leveraging passenger friendliness and comfort would mean to emphasize *Electrical Power Output* and *Noise*

Level for the engine, hence stressing *PRESSURE*, *DRAG*, *WELDABILITY* and *ADAPTABILITY* (the latter is explained by the need of providing room and support for larger electrical generators).

Figure 6 Local Value Drivers rank weights for alternative VCS

5.2 EVOKE Input Matrix

In the *Input Matrix* the IMC was divided into 6 main constituent parts, whose ECs were set independently. These parts were (Figure 7):

Mount Lugs (ML), *Outer Fan Case (OFC)*, *Outlet Guide Vanes (OGV)*, *Thrust Lugs Support (TLS)*, *Hub Outer Wall (HOW)* and *Hub Inner Wall (HIW)*.

Figure 7 Intermediate Case (IMC) main parts

A total of 3 design options were considered to demonstrate EVOKE's concept scoring capabilities. While the *baseline* design largely mirrors an existing product, *Option #1* and *Option #2* represent more radical innovations. They differed from the *baseline* mainly in terms of material, geometry and implementation of a bleed-air off-take function. The three sub-system

concepts were detailed in the *Input matrix*, with information about geometry, shape, material, reuse of technology, production lead-time and accessibility to experts. In total, 56 ECs were chosen to represent the difference between the *baseline* and the innovative designs. An extract of the *Input matrix* is shown in Table 1.

Table 1 Extract from the IMC Input matrix (Mount Lugs)

Engineering Characteristic (EC) of Mount Lugs	Units	Baseline (aluminum alloy engine mount)	Option #1 (titanium bolt engine mount)	Option #2 (titanium bolt engine mount)	Upper boundary	Lower boundary
Thickness	mm	45	45	50	80	30
Housing for additional components	m ³	0.3	0.3	0.35	0.8	0.2
Production lead time	min	180	180	230	300	150
Production line commonality	%	50%	50%	48%	70%	10%
Reuse of technology	%	65%	50%	45%	80%	30%
Availability of expert knowledge	%	65%	65%	60%	75%	45%

5.3 EVOKE CODA Matrix

The *CODA Matrix* was used to map the 56 ECs against the 10 sub-system VDs. The underlying logic of the mapping process is illustrated in Figure 8, which presents an extract from the matrix featuring 3 VDs and 1 EC. As an example, the EC *Surface finishing* (expressed as friction coefficient) features a strong correlation (0.9) with DRAG, a weak correlation (0.3) with MANUFACTURABILITY and a minimal correlation (0.1) with KNOWLEDGE REUSE. In the case study, the 560 intersections were resolved in 79 strong, 115 weak and 79 minimal correlations, plus 287 blank cells. Each coefficient was tagged with a

Knowledge Maturity score (from 1 to 5), to express the confidence of the design team when setting such correlation. A Relationship Type further detailed the VD vs. EC intersection. For instance, DRAG is improved when the friction coefficient is minimized, MANUFACTURABILITY when it is maximized (better surface finishing requires longer production lead time and a high expertise to be executed) and KNOWLEDGE REUSE when optimized (which is, when tolerances are similar to those of existing products). Eventually, 160 Max, 105 Min and 10 Opt functions, with related neutral and optimum points, were set, and assessed from KM perspective.

		Surface finishing			Relationship type (Max-Min-Opt-Avo)	Merit value
		Value	Upper limit	Lower limit		
		0.11	0.15	0.01		
		Correlation (0-0.1-0.3-0.9)	Neutral or optimum point	Tolerance (only for Opt and Avo)		
DRAG	14.75%	0.9	0.08		MIN	39.6%
MANUFACTURABILITY	13.22%	0.3	0.08		MAX	61.44%
KNOWLEDGE REUSE	3.89%	0.1	0.03	0.02	OPT	10.44%

Figure 8 Extract of the CODA matrix

As prescribed by CODA, the individual merit value for *Surface finishing* vs. DRAG is calculated for the minimization function using Equation (1):

$$f_{\text{Min}}(0.11) = 1 - \frac{1}{\frac{0.08}{2^{0.11}}} = 39.60 \quad (1)$$

Looking at *Surface finishing* vs. MANUFACTURABILITY, the maximization function uses Equation (2).

$$f_{\text{Max}}(0.11) = 1 - \frac{1}{\frac{0.11}{2^{0.08}}} = 61.44 \quad (2)$$

This task is repeated in all relevant intersections. Once design merit scores are

obtained for all sub-system VDs, their weighted sum renders a total score for a design.

5.3 Comparing IMC Design Options

Figure 9 shows the EVOKE results for the two innovative design concepts, the *baseline* and the *target*, detailing their value contribution for each sub-system VD. By changing the engine value dimension weights in the VCS, different winners are highlighted in the calculation.

Figure 9 EVOKE results for 2 competing VCS

A Performance-oriented VCS points to Option #2 as the most value adding, while a Comfort-oriented strategy indicates Option #1 and the *baseline* as preferable solutions. If a satisfying combination of ECs is found, the team must decide whether to invest resources in optimizing such a combination, communicating this information to the systems integrators, or to rework critical areas necessitating higher value contribution. KM, which is computed from the CODA matrix, further indicates how much the design team may trust the results of the EVOKE method.

In the first scenario, the results suggest the design team deepen the analysis and to raise the maturity of the knowledge related to Option #2. They further suggest refining its description to get closer to the *target*, mainly by trading-off excellent performances in some areas with those that necessitate higher value contribution (e.g., WELDABILITY and ADAPTABILITY). In the second scenario, all options are likely rejected because too far from the *target*, and design concepts will be radically redefined. Information about the winning options (in form of a list of ECs and their expected value contribution) is eventually fed back to the system integrator and the process iterated.

5.4 EVOKE Implementation

The EVOKE mathematical core was prototyped in MS Excel[®]. Valuation results for each part of the IMC assembly were further imported in a Product Lifecycle Management (PLM) environment, translated into colors by the use of a simple algorithm, and eventually associated to the IMC geometrical model. Value visualization capabilities were demonstrated in

SIEMENS TeamCenter/NX[®] using the HD3D Visual Reporting[®] tool (Bertoni et al. 2014).

In order to enable the sharing of evaluation results in the aerospace supply network, a feasible approach from a technological point of view is to treat the EVOKE methods and models as a black box, i.e. exposing only inputs and outputs of the calculation without exposing its underlying mechanism or logic. The use of Vanguard Studio (<http://www.vanguardsw.com/>) was explored to implement such a black box concept. Vanguard Studio is a commercial software package dedicated to graphical and hierarchical model development, which also incorporates automatic web deployment capabilities. Models can be automatically converted into a web service, allowing a client (a company that is part of the virtual enterprise) to access a value model implemented by another company by just calling them through their associated Uniform Resource Locator (URL). This allows model developers to publish their models so that they can be viewed and run by other users through a standard browser.

6. Verification

6.1 Sensitivity Analysis of EVOKE Method Matrixes

EVOKE was initially tested for sensitivity (Takai and Kalapurackal, 2012) following the approach proposed by Ghiya et al. (1999). Different correlation scales were tested in the *Weighting* and CODA matrixes for 5 relevant VCS, de-emphasizing the importance of strong and weak relationships. The test shows that the EVOKE results are mostly not impacted by changes in the correlation scale. The largest route mean square is recorded when the scale is

changed from 0,9-0,3-0,1 to 0,9-0,3-0,0, while in all other cases it reaches a maximum of 1,02%. In the extreme situation of setting the rank-weight of a VD to 100%, while setting all the others to 0%, the 0,9-0,3-0,0 renders a different ranking of the design alternatives, while the 0,4-0,2-0,1 scale only causes a small increase in route mean square (1,19%). These results are aligned with similar sensibility tests on correlation scales for quality function deployment (Iqbal et al. 2014, Olewnik and Lewis 2008).

6.2 Qualitative Verification of the EVOKE Method Application

Case study activities were followed up by interviews with practitioners and industrial experts, to gather feedback about the EVOKE process application in complex system design. EVOKE was appreciated for its ability to systematically capture value aspects embedding through life issues. Practitioners acknowledge that engineering models used at the company today are mainly focusing on performance optimization and costs drivers reduction. The latter is claimed to hinder designers from rationally assessing the benefits of a design option: as an example, increasing the weight of an aero-engine part will certainly lead to increased fuel costs, but may also result in lengthened maintenance intervals and reduce costs that way. EVOKE, by linking engineering characteristics with strategies for ‘value creation’ is acknowledged to go beyond performance- and cost-based metrics, encompassing the evaluation of utilities and more intangible aspects.

Elaborating on the main benefits of introducing EVOKE, industrial experts point to its ability of stimulating design team members to

confront each other on what ‘value’ means, from the standpoint of their different disciplines. This explains why detailed value functions and silver bullet models are not an answer for the needs of early stage decision makers. In a cross-functional team setting, such as the one featured in the case study, value models need to be generic enough to be grasped by those stakeholders without a technical background, and specific enough to enable benchmarking of alternative concepts with sufficient confidence and detail.

6.3 Qualitative and Quantitative Verification of Key Model Constructs

The EVOKE method was further qualitatively and quantitatively verified in ad-hoc design episodes involving industrial practitioners. Verification was performed in 2 stages, both aimed at verifying the ability of the cross-functional design team to work with both ‘functions’ and ‘coefficients’ compared with merely the latter (as in traditional QFD).

The first activity was performed at the partner’s company site, and involved 45 participants among engineers, managers and process leaders, who were divided into 13 groups. A major challenge with verification in the proposed case study was related to the limited availability of the target group. Hence, when creating the design episode, the authors choose to frame the use of the EVOKE method within a simple and recognizable problem statement. This choice addressed the needs of both maximizing the time dedicated to working with the EVOKE matrixes, and minimizing the time needed for understanding boundaries and objectives of the activity. The design episode featured the prototypical design problem of selecting a bike

wheel concept able to optimize the value of the entire 'bike system'. Participants were asked to populate the *Weighting* and *CODA* matrixes to analyze alternative bike wheel options. This activity was limited to setting correlation coefficients and functions: researchers provided neutral, optimum points and tolerances. The bike wheel example was chosen because readily recognizable by all participants. Also, participants were knowledgeable and had first hand experience of the interactions between the system and its parts. Furthermore, designing sub-systems for bikes is a typical problem in product development literature. Bike suspension design is the reference example in the 'Product Specifications' chapter in Ulrich and Eppinger (2008, p.77). Also, the case of designing of an anti-spraying device for bike wheels is recurrent in Ullman (1992, p.105) to exemplify the use of concept design tools.

A Likert-scale questionnaire was designed to gather qualitative feedback from the industrial practitioners on issues related to setting correlation coefficients, non linear-type functions, and knowledge maturity scores in the matrixes (Figure 10).

In order to verify the suitability of the method for different cross-functional team members, the answers were divided based on the role of the

respondent in the company. The three groups, namely engineers, managers and process leaders, acknowledged that it was relatively easy to reach an agreement when setting correlations, with process leaders being the ones with fewer concerns. They were also the ones feeling most comfortable with the exercise, while managers and engineers expressed concerns about the easiness of the approach. The mechanism of setting non-linear functions was best understood by engineers and process leaders, with the latter feeling pretty comfortable with the task of setting Max, Min and Opt functions, while managers were more negative towards the approach. The use of KM to support concept evaluation activities was most appreciated by engineers and managers. Furthermore, participants expressed a weak positive feeling in terms of easiness in setting KM values. Overall, most of engineers perceived EVOKE results to be intuitive, although a few expressed only a weak positive feedback. Managers and process leaders were more split in their judgment, but positive feedback prevailed. Eventually, the three groups were aligned in the way they consider their overall experience with EVOKE: about 80%, 90% and 70% of the engineers, process leaders and managers, 'agreed' or 'weakly agreed' that the results from EVOKE were satisfying.

Figure 10 Results from the Likert-scale questionnaire

Later, the authors conducted a quantitative analysis of the 700 coefficients in the *Weighting matrix* and 400 coefficients (and functions) in the *CODA matrix*. The groups were expected to be able to identify very similar coefficients/functions (ideally the same) at each intersection in the 2 matrixes. Very different

coefficients and opposite functions would indicate that CODA logic is ambiguous and that the results of the value assessment is significantly biased by the ability to work with the matrix. Table 2 shows the results from the quantitative analysis.

Table 2 Results of the quantitative validation

Agreement on:	Description	Weighting matrix	CODA matrix
1 coefficient	The teams model an intersection using a single coefficient (e.g., either 0.9, 0.3, 0.1 or 0).	59.43%	56.75%
2 consecutive coefficients	The teams model an intersection using coefficients closed to each other (e.g., either 0.9-0.3, or 0.3-0.1, or 0.1-0).	83.43%	84.00%
1 function	The teams model an intersection using a single function (e.g., either Max, Min or Opt).	N/A	61.24%
non-opposite functions	The teams model an intersection with either Max-Opt or Min-Opt functions	N/A	86.22%

Most of the teams were able to identify coefficients and functions close to each other, in similar percentages in the two matrixes. Still, several groups failed in recognizing the meaning of Min vs. Max functions within specific intersections, and have struggled when setting Opt-type functions.

In a second experiment, 21 practitioners worked with the design of an aero-engine assembly, and were asked to populate the CODA matrix with both correlation coefficients and non-linear functions. They were also asked to express their level of confidence in such choices. This feedback was gathered using a Visual Analogue Scale (VAS) (Wewers and Lowe 1990) technique. The results from the analysis of 296 intersections showed that, on average, the level of confidence in setting correlation coefficients (67,89%) and functions (73,14%) was similar. These results show that the effort needed to agree on a function is similar (or even slightly minor) than that of setting correlation coefficients. This seems to indicate that the use of non-linear functions is not detrimental for the overall trustability of the value models result (i.e., functions can be identified

with at least the same level of confidence as correlation coefficients, and are not just ‘educated guesses’).

7. Discussion

The EVOKE method provides novel capabilities with respect to information sharing and requirements elicitation in early system design. The argument is that the ability to understand design intent and value contribution of engineering characteristics early in the process contributes to reduction of development lead-time, both at system and sub-system level. For instance, the need of an airline ‘to be known for the passengers first’ can be translated at aircraft level in value drivers such as ‘cabin air quality’, ‘cabin noise level’, and ‘seat spacing’, ‘cabin lighting’ or ‘vibration level’. This initial selection can be communicated in a first iteration of the VCS to the engine level. Here, the ‘cabin noise level’ VD can be translated, into more detailed drivers, such as ‘engine noise level’ and ‘engine vibrations’, and further cascaded down to sub-system manufacturers. At this level, EVOKE enables the design team to play with the strategy

for value creation communicated from the top, elaborating and evaluating solutions based on this.

A first main advantage is that the value content of innovative solutions becomes more tangible in an early stage, compared to a more traditional requirements decomposition process. The system level contribution of a solution can be better quantified, not being just an expression of gut-feelings and intuition. Misconceptions can be minimized together with the risk of investing on sub optimal designs efforts. Also, EVOKE supports the execution of quick WHAT-IF analysis to evaluate the effect of a design on the satisfaction of stakeholders' needs for changing VCS. This is important, because in reality it is likely that a VCS evolves and matures over time, or that several conflicting VCSs exist at the same time in the extended enterprise. The EVOKE method facilitates the design team in quickly finding out the most valuable solution for any possible instantiation of the VCS, thus spotlighting emerging phenomena at changing boundary conditions, mitigating risk. It shall be noticed, however, that EVOKE works best when the high-level functional description of a sub-system is already defined. Variants are instantiated from an existing product platform, adding information about geometries, materials and other characteristics, in an iterative fashion. This poses an intrinsic limit to the variability of the design that can be described and processed using the EVOKE matrices. This limit is set by the level of granularity of the platform description used as reference.

Verification activities show that EVOKE matches specifications and assumptions deemed acceptable for the given purpose of application (Schlesinger 1979), also considering that no

training session to 'teach' EVOKE was performed prior to testing. Still, populating the *Weighting* and *CODA* matrixes is far from being a trivial task, also because the 'design merit' scores resulting from the CODA calculation are very sensitive towards exact values of neutral and optimum points. Any mistake here can lead to unwanted gaps between design options, especially when the tolerance is small.

For this reason, Knowledge Maturity was appreciated as a means for improving decision makers' awareness. Those taking part to verification activities recognized the 'value' of capturing the maturity of assessments made, and KM provided a straightforward approach in this respect. KM is de facto a shared artifact that allows the team to negotiate a shared understanding of the advantages and drawbacks of the knowledge base. A KM model is also a practical tool to highlight areas in the value model where additional knowledge needs to be gathered to perform a more reliable assessment. Adding a KM perspective to the value analysis results might lead decision makers to discard an identified optimum in favor of a combination of ECs that renders a higher maturity score. However, improvements are needed in the way the generic scale is defined and in the way the total maturity score is computed. Excellent maturity in some areas can be degraded by no information on other areas, and this affects the model's reliability. Eventually, guidelines shall be provided to support the design team in increasing the maturity of available information.

7. Conclusions

Nowadays, SE modeling work bounces back and fourth between two extremes. Engineers are

in need of models able to more systematically capture the value of their solutions, and to use them to perform optimization work. At the same time, systematization shall not impede transparency and trustability. The model's underlying logic shall be understood outside the specific role of the system engineer, in order to negotiate system features across functions and levels of the supply network. Compared with existing valuation methods in SE, the EVOKE method and related operational tools propose a possible trade-off to cope with this issue. Current experimental work, featuring the analysis of protocols in design episodes (Panarotto et al. 2016) shows that EVOKE matrixes are more effective boundary objects than requirements checklists when dealing with early stage system design activities. The matrixes are therefore plastic enough to adapt to local needs, yet robust enough to maintain a common identity across sites.

An important feature introduced by EVOKE is the use of the VCS construct to configure the engineering studies by ranking and down-selecting needs of particular interest. Decision makers and program managers can exploit this feature to set expectations of the study results, and to communicate to the design teams 'why' a study is needed. This complements the more technical pre-conditions necessary in the specific context of system design.

The EVOKE method makes explicit that the objective of early system design is not that of engineering a system, rather than of creating awareness and consensus on solution directions. Still, by insisting on capturing and formalizing tacit knowledge in 'numbers' and 'trends', it supports a more concurrent and collaborative

requirement establishment process, and ensures that a value focus is retained throughout the subsequent development work at all levels. In turn, this can reduce rework that originates from misinterpretations of requirements and sub-optimal designs, as well as improve the sub-system provider ability to contribute with innovative content to the definition of the overall system.

Future developments of the EVOKE method and tools will need to balance modeling detail (to make results more realistic and trustable) vs. simplicity and interaction, to leverage the 'boundary object' effect (Carlile 2002). Also, they need to better consider the dynamic behavior of industrial and ecological systems. Rather than to picture a static outcome, EVOKE shall provide support for the analysis of future scenarios. Leveraging Epoch-Era analysis (Ross and Rhodes 2008) in the modeling activity is seen as the next step forward in this direction. Epoch-Eras will be defined by the design team, reflecting changes in preferences, technologies, environments, and system offerings, and mirrored in separate EVOKE models. A main benefit of doing so is the ability of assessing the 'value robustness' of proposed system design concepts in the forecasted scenarios. Further improvements also foresee the introduction of both convex and concave functions for maximization and minimization.

From the point of view of leveraging communication among design team participants, several industrial case studies are currently conducted to understand what visualization means are preferable to display the EVOKE results in decision gates (Bertoni and Bertoni, 2016). The authors have previously developed

and tested color-coded 3D models to translate value analysis outcomes into visual features in a CAD environment (see: Bertoni et al. 2014). The work continues today to understand how to seamlessly integrate EVOKE results with the outcomes of structural/cost-related simulations, at different levels of granularity.

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