VALUE-DRIVEN ENGINEERING DESIGN: LESSONS LEARNED FROM THE ROAD CONSTRUCTION EQUIPMENT INDUSTRY

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Abstract

Value models, in form of economical optimization functions, are often proposed to frontload engineering design activities. However, literature argues that, when qualitative data and assumptions prevail, a qualitative assessment of the 'goodness' of a design is preferable against a numerical (and monetary-based) encoding of preferences. This paper explores how a model-based approach can support deliberation about value in cross-functional design teams. Emerging from case studies in the road compaction equipment industry, the paper analyzes preferences for value modelling support when it comes to iteratively translate customer desires into terms meaningful for engineering design decision-making. It further prescribes a framework 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, moving from qualitative to quantitative. The findings highlight the role the proposed chain of value models plays in terms of providing a shared reference to stimulate value discussions across functions and organizational roles, which is something that does not naturally happen in the organization today.

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1 INTRODUCTION AND OBJECTIVES

A problem-solving perspective is fundamental to product development and engineering design (see: Dieter and Schmidt 2013, p.126; Pahl and Beitz 1996, p. 46). Literature (e.g., Ullman 2015) recognizes that solving problems becomes, on average, increasingly expensive and time consuming as development projects progress, and financial commitments are made. Thomke and Fujimoto (2000) show how practitioners are coping with this issue by reengineering their development processes to move or 'load' their problem identification and solutions generation – by means of project-to-project knowledge transfer, digital mock-ups or advanced simulations - backward in time, to what is called the 'front' of the process. Systems Engineering (SE) research has stressed the importance of a specific model type to frontload engineering design activities with: the value model (Collopy and Hollingsworth 2011). This is explained as design decision support that increases awareness of how much customers 'value' certain capabilities against each other, so to orient trade-off resolution towards value maximization. The use of such models in early design is justified by observing that requirements decomposition activities lead to progressive opaqueness of the initial intent of a design (Isaksson et al. 2013). Hence, design solutions might not be able to fully meet customer and stakeholder expectations even if requirements are met: engineering practices merely facilitate finding a feasible solution, and do nothing to identify the best solution (Soban et al. 2011).

Value models are often described as monetary optimization functions (Collopy and Hollingsworth 2011), but this description challenges the frontloading exercise. Firstly, value provision objectives are often of less tangible nature than technical system performance targets (see: Vargo and Lusch 2004), which means that deterministic models may be perceived of little significance in early design (Soban et al. 2011). Secondly, it is unlikely to have full data available to populate the proposed optimization functions in such an early stage. Even if available, data are unlikely to be shared by partnering organizations when working in a mode of coopetition (Isaksson et al. 2013). Even if data could be shared and deterministic vale models built, only individuals with engineering background might be able to use them as 'communicative device across' in a cross-functional team setting (Bertoni et al. 2016). Upon these considerations, the paper investigates the following research question:

How can a model-based approach support deliberation about value in cross-functional design teams?

The above links to a central issue in the Value Driven Design (VDD) research agenda (Soban at al. 2011), which concerns how value models shall iteratively translate customer desires into terms that are meaningful for engineering design decision-making. This paper argues that the benefit of such models lies, rather than in the model itself, in the set of activities by which they are iteratively discussed, prototyped and refined. The objective is then to present a framework 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, moving from qualitative to quantitative. The proposed framework is exemplified and discussed within a case study related to the design of a new asphalt compactor.

2 METHODOLOGY

The research can be described as of Type 5 in the Design Research Methodology (DRM) framework (Blessing and Chakrabarti 2009, p.60). It features a review-based Research Clarification (RC) stage, comprehensive Descriptive Study I (DS-I) and Prescriptive Study (PS), and an initial Descriptive Study II (DS-II). Here, 'quality of the final product development outcome' and 'reduction of rework due to misunderstood requirements' were considered main 'success criteria' (Blessing and Chackrabarti 2009), which were further cascaded down to more 'measurable criteria' to make sense of the role of 'value' and 'value models' in cross-functional decision making. For this reason, the dynamics of the engineering team, rather than the 'value model' or the behavior of single individuals, is considered main unit of analysis (Yin 2003, p.40) for the study.

Research is conducted in close collaboration with a Swedish multinational engineering subsidiary manufacturer of mobile compactors for road surfaces. It features 'few-focused case studies' (Voss 2002) to build theory on the topic of value-driven engineering design, identifying key variables, describing their linkages and why relationships exist. The main aspect of interest in the empirical data gathering stage was to understand the role 'value' has in the collaboration between different expertise in the organization when dealing with early stage design decision making. The primary mode of data collection was semi-structured interviews. A total of 12 respondents were sampled across cases, covering a variety

of roles, from managers to CAD engineers, from marketing to information technology experts. They were located using a snowballing technique (Warren 2002): those initially fulfilling the theoretical criteria helped in locating others through their social network, to cover both the 'meatiest' cases and the 'peripheries' (Miles et al. 2014). The initial interviews were transcribed and validated by each respondent. Follow-up interviews and requests for clarification were documented by means of handwritten notes. In these interactions, visual demonstrators of emerging modelling concepts, were used to identify critical topics for value modelling. The analysis of internal company documentation (aided by the part time physical presence of one researcher at the company facilities) and regular multi-day co-creation workshops were used as triangulation method.

3 TRANSLATING CUSTOMER DESIRE INTO VALUE MODELS: A REVIEW

3.1 Value models as quantitative value functions

Miles (1972) is among the firsts to introduce the value analysis concept: a product or service is considered to have good value if it displays appropriate performances associated with low cost. In this definition value is treated as a deterministic parameter resulting from a given value 'function'. Total Cost of Ownership (TCO) and Life Cycle Costing (LCC) build on Miles' theory with the scope of 'reengineer' the purchase price of new products or services, including more and less obvious issues (e.g., Dimache et al. 2007). TCO and LCC have been criticized (Price et al. 2012) for leading to false perceptions of what value is for an engineering system, mainly because they lack of considering all relevant 'ilities' (see: McManus et al. 2007). The research stream of VDD (Collopy and Hollingsworth 2011) stresses the latter, and proposes progressive refinements of a so-called 'surplus value' equation to optimize a system configuration from a lifecycle perspective. However, Collopy (2012) itself raised concerns about the trustworthiness and usefulness of such function, due to its inability of considering subjective phenomena. Monceaux et al. (2014) and Siyam at al. (2015) further claim that a surplus value modelling is only suitable for detailed design, being too data intensive for the conceptual design phase. Equations such as the one proposed by Lindstedt and Burenius (2006) aim to cover this gap. By defining customer value in the broader perspective of 'perceived customer benefit', including intangibles (Desmet et al. 2001), divided by the 'use of customer resources' (money, time and effort), they attempt to bridge quantitative with more qualitative assessment.

3.2 Value models as qualitative criteria for multi attribute decision making

The VDD research agenda (Soban et al. 2011) acknowledges that, when qualitative data and assumptions prevail, a qualitative assessment of the 'goodness' of a design is preferable against a numerical (and monetary-based) encoding of preferences. Product development and engineering design literature often present examples of qualitative criteria for multi attribute decision making (MADM) (e.g., Roozenburg and Eekels 1995, p. 332; Pahl and Beitz 1996, p. 178; Wright 1998, p. 139, Ullman 2002, p. 176, Ulrich and Eppinger 2012, p. 209), which typically precedes more deterministic assessments (e.g., Roozenburg and Eekels 1995). While literature agrees about the overall process by which these criteria are extracted by the initial need list, there is little guidance with regards to which aspects of the product lifecycle shall be prioritized to capture customer and stakeholder value in its fullest. The 'main headings' for design evaluation proposed by Pahl and Beitz (1996, p. 179), and the hierarchical structure of needs (primary, secondary, tertiary) proposed by the Voice-of-the-Customer theory stands out in this respect, Value Proposition Canvas (VPC) (Ostervalder et al. 2014) is another major reference in the quest for a systematic framework from which qualitative value criteria shall be defined. VPC proposes Customer Gains and Customer Pains as main categorization. The first gathers customer's benefits and desires, spanning across personal, functional, or economical dimensions. The latter collects all negative emotions and undesired costs, situations and risk that customers could experience before, during and after getting the job done. The Design Thinking methodology (Leavy 2010) provides another mental model to derive value criteria, which is expressed as intersecting 'constraints' in the so-called Feasibility-Viability-Desirability (FVD) framework. The Triple Bottom Line (TBL) framework, featuring 'social', 'environmental' and 'financial' performances, is also proposed to measure companies' business value (Willard et al. 2012).

4 PREFERENCES FOR VALUE MODELING SUPPORT IN EARLY DESIGN

The Knowledge Value Stream (KVS) - Product Value Stream (PVS) model (Kennedy 2008) was used as guiding framework (in the way proposed by Isaksson et al. 2015) to organize the DS-I findings around the topic of 'model-based support for value'. The model recognizes the innovation process at the company belonging to two value streams. The KVS represents the capture and reuse of knowledge about markets, customers, technologies, products and manufacturing capabilities 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. Table 1 summarizes preferences for value modelling support as emerged in the case studies.

Table 1. Preferences for value modelling support

In the Knowledge Value Stream (KVS)	In the Product Value Stream (PVS)
Creating pointers to all significant value aspects (tangible and intangible) to be captured.	Extending monetary awareness beyond manufacturing costs and performance.
Fostering rationale and context awareness.	Learning about problems and alternatives.
Providing a basis for negotiation and cross-pollination of knowledge across disciplines.	Building understanding through associative processing.
Providing a hub to systematically capture knowledge and argumentations.	Building understanding through the use of a common language.
Preparing the decision base for gate meetings.	Learning about the dynamics of value creation.
Building the basis for value quantification.	Supporting quantification of 'softer' value aspects.

4.1 Preferences in the Knowledge Value Stream

Uncertainty and ambiguity in KVS means that value models shall work as 'catalysts' for knowledge generation and negotiation, rather than mechanisms to automate the decision-making process. Value analysis in the KVS loop shall not intend to dig deep in the quantification of value, rather its outcome shall mainly be that of directing the team towards preferred solution principles. The modelling activity shall not pretend to give designers a clear-cut answer to their problems, but rather to preserve ambiguity and highlight trends. To catalyze all relevant value-related knowledge for KVS tasks, model-based decision support shall help design teams in reviewing all those significant aspects of value, tangible and intangible, that are worth considering given the stated design objectives. Such aspects shall span through the whole system lifecycle, consider heterogeneous customer and markets, as well as contemplate alternative future scenarios. Providing a systematic and exhaustive framework of 'value' is considered important also to identify disciplines that need to be involved in the innovation process. Interview respondents acknowledged that a better understanding of customer value can only be gained though collaboration and communication with experts from other organizational functions. In the analyzed case studies, activities in the KVS were described to be rarely fully collaborative: needs and expectations are gathered by different functions and translated into system requirements without the necessary negotiation.

This points to model-based support able to stimulate design team members in expressing their different opinions and to confront each other when perceptions differs, for instance with regards to the relationship existing between value and requirements. An opportunity is identified here with regards to shape the model-based support as a hub where argumentations related to 'value' of solution concepts can be systematically captured. Respondents believe that the activity of clarifying the underlying context and intent of design requirements, as well as the rationale behind a given list of specifications, shall be actively supported during the entire analysis and synthesis cycle of activities conducted ahead of the decision meeting (i.e. stage). As stated by one of the respondents:

"It becomes a matter of daring to define them [Author's note: relationships between solutions and value], then you can always change these relationships. But if you have them defined it becomes easier to point at them. It is a matter of systematically doing it while you work, I think it is a big benefit".

Argumentations captured during the 'stage' would greatly enhance the decision base for gate meetings. This knowledge base would also contribute to define more explicit relationships between the original stakeholders' needs and expectations and the properties of a product, which would then facilitate the subsequent PVS discussion on the appropriate quantification strategy.

4.2 Preferences in the Product Value Stream

Decision gates in the PVS are found to be better supported if value aspects are quantified in monetary terms, which means that the quality of the assumptions made in the KVS must be backed-up with evidence-based statements. TCO models used by dealers (e.g., to simulate, discuss and reason with customers about what machine to buy) were often referred to by respondents to exemplify how value models shall work in conceptual design: the objective shall be that of extending monetary awareness beyond costs, promoting a stronger focus about all monetary benefits of a solution:

"we shall simulate and assess the value of different sub-systems and to set the selling price after that, rather than setting the price after the manufacturing costs. And to do that during the development, not just when you are sitting with the customers and motivating the price."

Practitioners also highlighted the difficulty of influencing decision-makers when discussing soft value aspects, mainly because engineers require 'numbers' when making design trade-offs. Value models at this stage shall then be able to monetize even the most intangible aspects of the solution. The problem of valuing the 'visibility' of an asphalt compactor operator well exemplifies this need:

"If you take visibility, we define the benefit of having a good visibility on the machine as the ability to drive faster when doing compaction following an edge [...] then we agreed that it is the only thing that plays a role. After that, we can describe an operational case and estimate functions for visibility, so you can simulate and see what it can be worth, in terms of money."

The learning function is found to be crucial also in the PVS. Even if product descriptions are more mature, and uncertainty mitigated, a 'grand total' is hard to trust, mainly because it is difficult to assure the exact monetary correctness in every sub-function. The role of model-based support in this respect is that of iteratively learn-by-doing about the dynamics of value creation. Hence, respondents highlighted that value models do not need to be accurate to be effective. Their purpose shall not always be that of producing a grand total, but rather to firstly highlight go/no-go areas, and then to spotlight relative differences with a baseline solution, to be refined at each iteration. Still, PVS activities ask for more fact-based evidence ("digits rather than trends") so that intangible value creation aspects can be benchmarked against more classical cost, performance and weight requirements. Practitioners mentioned the benefit of a 'pool' of representations that mix deterministic and qualitative aspects. Observing the convergence between the different models would help in building more understanding of problems and solutions through associative processing. This 'pool' would also facilitate discussion in the cross functional team, with some models being generic enough to be grasped by those stakeholders without a technical background, while others being specific enough to benchmark of alternative concepts with sufficient confidence and detail.

5   THE GENERIC PROCESS FOR VALUE-DRIVEN ENGINEERING DESIGN

The generic process for value-driven engineering design (Figure 1) is a main result of the Prescriptive Study. It is shaped on the KVS-PVS framework and features 5 steps prior to design decisions. The steps are organized in 2 assessment loops, both qualitative and quantitative. Each step in the process is described in the sub-sections below, and further exemplified in a case study related to the design of a subsystem for a 9-ton asphalt compaction machine.
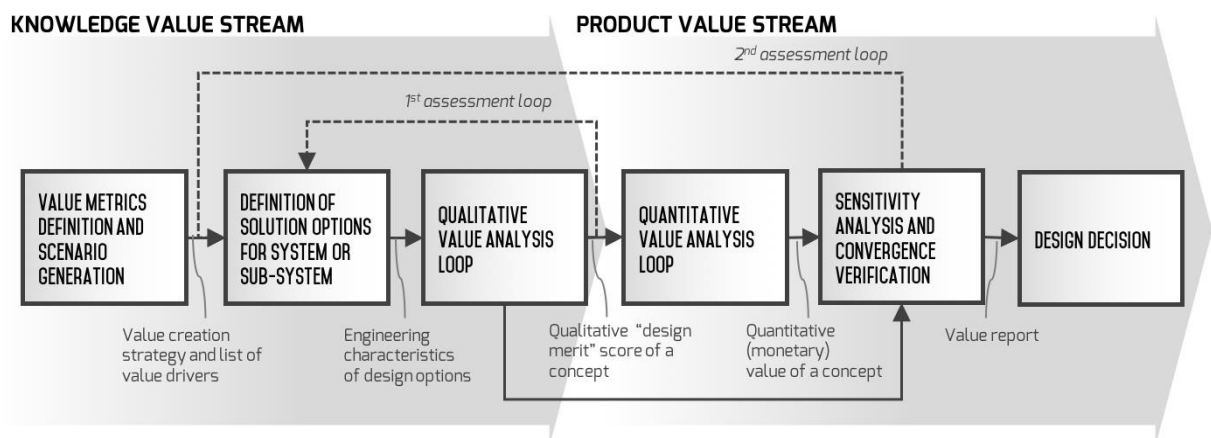

Figure 1. The generic process for value-driven engineering design

5.1 Value metrics definition and scenario generation

The FVD framework (Leavy 2010) is used in the KVS to define qualitative MADM criteria guiding the first value assessment loop in the value-driven engineering design process (see Figure 2).
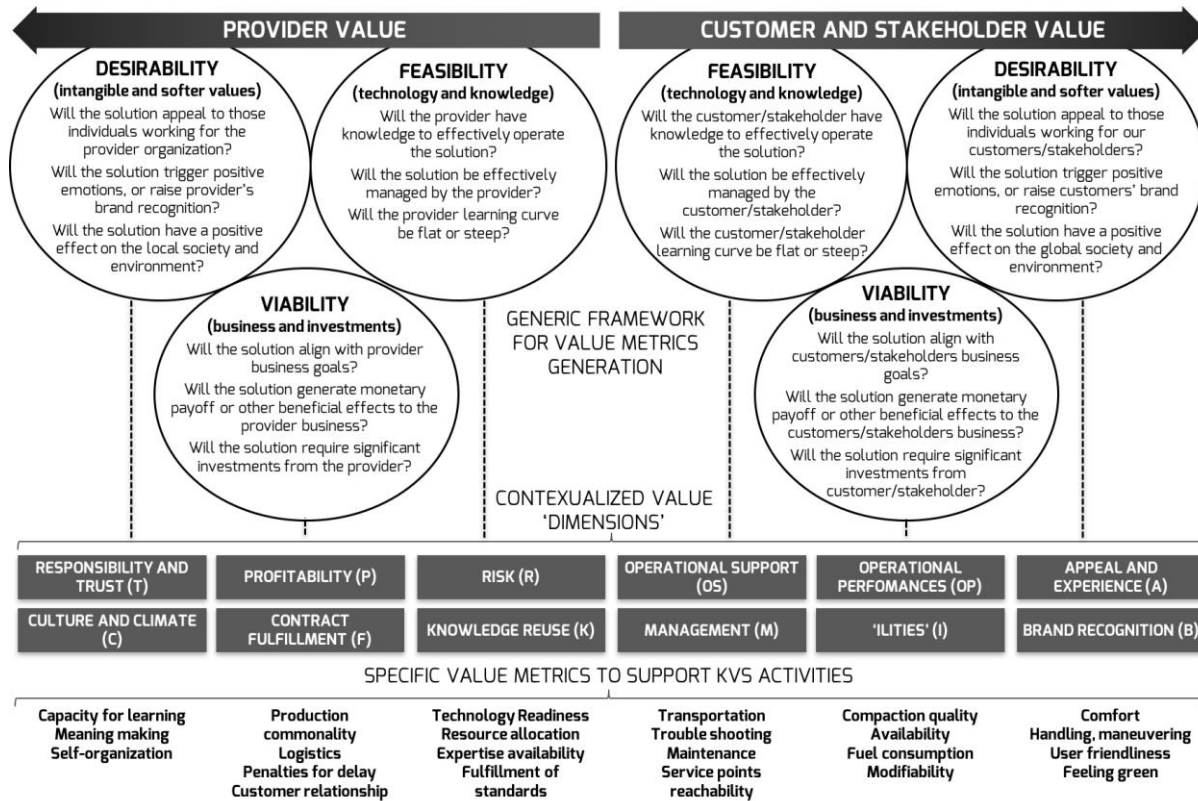

Figure 2. The generic process for value metrics definition applied to the case study

Value creation is considered both from a customer/stakeholder and provider perspective, rendering 6 generic value areas. A 'platform' strategy well exemplifies this dichotomy: a product might be non-optimal for the current list of customer needs, still it might enable economies of scale, build provider's knowledge and raise technology readiness for future products. These areas are cascaded down to value 'dimensions', which are more contextualized criteria relevant for the project at hand. Studies on decision theory (Zanakis et al. 1998) suggest to further cascade these down to 20-30 specific value metrics (in a n:n relationship), which are rank-weighted using Analytical Hierarchical Process (AHP) (Table 2). Importantly, different strategies for value creation (e.g., referring to different markets or personas), emphasize different aspects of value, rendering different rank-weights for the metrics.

Table 2. Rank weighted value metrics (from AHP) in the case study (extract)

Value dimension	Value metrics	MARKET#1	MARKET#2	MARKET#3	MARKET#4
A, B, OP, T	Safety	*13,45%*	*9,28%*	*12,84%*	*11,45%*
A, OP	Handling/maneuvering	*5,45%*	*7,28%*	*3,41%*	*1,45%*
A, OP	Visibility	*1,45%*	*9,28%*	*3,6%*	*1,45%*
OP, B	Compaction quality	*14,45%*	*6,9%*	*11,51%*	*11,45%*
OP	Fuel consumption	*11,45%*	*9,28%*	*13,61%*	*13,45%*

5.2 Definition of solution options for system or sub-system

Four design options defined in the second step. Option #1 featured a design inspired by existing off-the-shelves solutions, and was used as baseline throughput the entire process. Option #2 introduced an incrementally improved sub-system, with only few dimensions differing from the baseline. Option #3 featured a radical solution, with significant cascading effects on the entire geometry of the machine.

Option #4 mirrored a sub-system offered by competitors. Each design has an impact on the operational behavior of the machine (i.e., the operator will follow different 'patterns' in compaction), intangibles aspects (comfort, visibility), and other lifecycle dimensions (availability, maintenance, repair, resale value). Engineering Characteristics (EC) are a preferred mechanism to describe these options in the qualitative value model. Bertoni et al. (2017) explain these as encompassing only those technical features (geometry, material) and lifecycle aspects (manufacturability, maintainability, recycling) that distinguish a new design from the baseline. Table 3 lists some of the EC defined for the 4 options, Upper and lower boundaries (for each EC) stimulate the cross-functional team in discussing the limits of the product platform, and ensure mathematical consistency of the CODA/EVOKE matrix functions.

Table 3. Engineering Characteristics (EC) for alternative roller sub-system design (extract)

Engineering Char.	*Unit*	*Baseline*	*Option 1*	*Option 2*	*Option 3*	*Upper B*	*Lower B*
Turning radius	mm	5620,00	5620,00	5010,00	7290,00	7000	5000
Operating Mass	Kg	7700	7777,00	7700,00	7500,00	9000	7000
Mass on rear frame	%	50%	50,5%	50%	50%	53%	47%
Volume of water tank	dm^3	700	720,00	700,00	700,00	800	600

5.3 Qualitative value analysis loop

In the qualitative value analysis loop the EC list is mapped against the rank-weighed value metrics to obtain a 'merit' score for each design. Both literature (e.g., Eres et al. 2014) and the empirical study point to the use of design support that is (1) transparent (2) able to realistically map the satisfaction-requirements relationship, (3) simple enough to trigger discussion with non-technical personnel, (4) systematic enough to prepare the basis for quantitative evaluation, and (5) able to provide a feedback on the trustability of the model. Quality Function Deployment (QFD) was early on identified as a strong candidate with regards to (1) and (3), but weak with regards to (2), (4) and (5) (Collopy 2009). These factors suggest extending QFD logic into the EVOKE model (Bertoni et al. 2017) (Figure 3). EVOKE exploits nonlinear functions to more realistically capture the relationship between customer satisfaction and system requirements (Liu and Boyle 2009), to satisfy (2) and (4). Nonlinearity is introduced by means of Minimization (Min), Maximization (Max), Optimisation (Opt) and Avoidance (Avo) type functions to satisfy (3) – hence avoiding introducing fuzzy logic, rough number or neural networks approaches. Knowledge Maturity (KM) (Johansson et al. 2011) was further introduced to explicitly communicate the uncertainty embedded in the model, hence to satisfy (5).

Figure 3. EVOKE matrix mapping EC and value metrics in the case study (extract)

In the asphalt compactor case (Figure 3) the EVOKE matrix featured 231 intersections, resolved in 25 strong (9), 24 weak (3) and 30 minimal (1) correlations, plus 151 blank cells. Also, 33 Max, 39 Min, 1 Avo and 7 Opt functions, with related neutral and optimum points, were applied.

5.4 Quantitative value analysis loop

Both literature (e.g., Fabrycky and Blanchard 1991) and empirical findings elucidate how cost shall be an active rather than a resultant factor throughout the system design process. The proposed quantitative analysis model builds on Neunes et al. (2008) and insists on a conceptual approach for lifecycle costing (see Gupta 1983), to raise awareness about the economic impact of alternative design concepts. The TCO equation showed in Equation (1) is derived from the work of Ferrin and Plank (2002). It was

implemented in MS Excel, and populated with information gathered from interviews with practitioners, internal working documents and other literature sources.

$$TCO = \sum_{i=1}^{n} \frac{(DEPc+FINc+OH)+(Fc+Oc+Sc+WMc+Rc+Lc+P\&F)}{(1+r)^i} + \frac{(DECc-RV)}{(1+r)^n} \qquad (1)$$

- DEPc: Capitalization of the acquisition cost of equipment over its economic life.
- FINc: Other financial costs such as interest on loans and taxation reduction.
- OH: Overhead costs, such as training, recruitment, logistic costs or insurance costs.
- Fc: Fuel consumption during compaction operations and transport/ relocation.
- Oc: Other machinery costs, such as for supporting equipment.
- Sc: Setup cost, i.e., for preparation and inspection of the machine before and after work shift.
- WMc: Wear, maintenance and planned service activities costs, such as labor, parts, downtime.
- Rc: Cost for unplanned interruptions (e.g., labour cost, spare parts or downtime).
- Lc: Logistic cost (e.g., equipment transportation, storage or parking).
- P&F: Penalties and fees cost, which may be delay-, quality- or accident-related.
- DECc: Decommissioning cost, in case the machine is not sold second hand.
- RV: Cash flow generated by selling the machine second hand.

Average yearly usage of the machine, purchase cost, fuel cost and labor cost were some of the key input parameters obtained at this stage, which are used to compute the TCO value for each design option. Other system performance characteristics, on which costs in Equation (1) depend on, were extrapolated using simulation models developed in the AnyLogic® software environment. These models link physical simulations at sub-system level to functional performances at machine level, and further to the machine operational performances, in a mix of different operational scenarios.

5.5 Sensitivity analysis and convergence verification

The last step in the process verifies sensitivity and convergence of both quantitative and qualitative modelling. EVOKE's model sensitivity in verified following the method proposed by Ghiya et al. (1999), while the robustness of the TCO model is tested against changing input parameters. (mainly: *fuel price*, *cost of labor*, *yearly usage*, *frequency of new road construction* and *discount rate)* to understand the range of input values for which the results shall be considered valid. Qualitative and quantitative findings are further displayed in a 'decision theatre' environment (Figure 4) to enable such analysis and to stimulate discussion about the meaning of the modelling results.
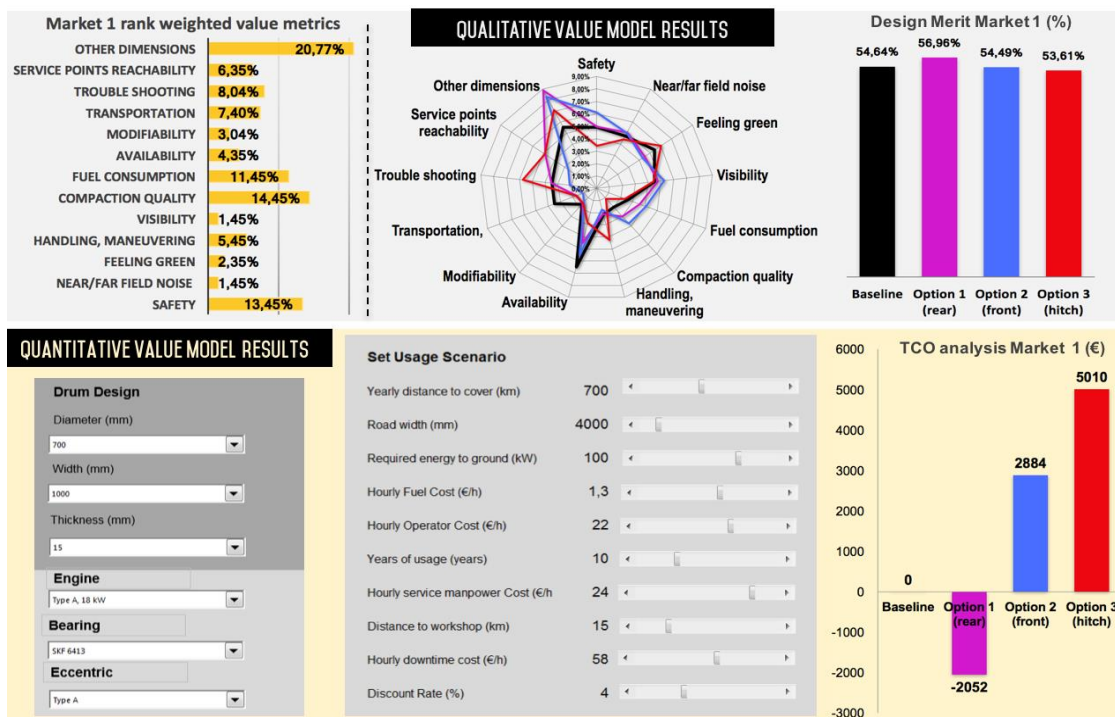

Figure 4. Value model results visualization in the convergence verification stage

6 DISCUSSION AND CONCLUSIONS

In situations where the 'system' to be engineered is becoming increasingly large and complex, processes and tools for value-driven engineering represent a step forward in the ongoing discussion about value orientation in requirement management. Practitioners recognize that in the fuzzy front-end engineers are lacking of tools to communicate why their work is 'good', and to deliberate about the most value-adding design. The proposed chain of value models is acknowledged to cover a gap when it comes to stimulate value discussions across functions and organizational roles, as well as to maintain focus on the underlying business case, so that individuals can build arguments for selling their innovative ideas, both externally and internally.

These results shall be considered a step forward towards a larger research effort, whose purpose is to capture and represent 'value' aspects in models within the engineering design process, which is something that does not naturally occur in the organization today. Future research will address the challenge of integrating value-based decision support in the ecosystem of tools that exist in today's engineering organizations. It will also aim to apply value models in more data-rich situations, as well to improve the visualization of modelling results. An interesting track is related to the use of data mining techniques to support decision makers in populating the value models. 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. Developing capabilities to organize such patterns would greatly enhancing the reliability and fidelity of value models at all levels.

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