

## MODEL BASED DECISION SUPPORT FOR VALUE AND SUSTAINABILITY IN PRODUCT DEVELOPMENT

Isaksson, Ola (1); Bertoni, Marco (2); Hallstedt, Sophie (2); Lavesson, Niklas (2)  
1: GKN Aerospace Sweden AB; 2: Blekinge Institute of Technology, Sweden

### Abstract

Decomposing and clarify “sustainability” implications in the same way as concrete targets on product functionality is challenging, mainly due to the problem of showing numbers and ‘hard facts’ related to the value generated by sustainability-oriented decisions. The answer lies in methods and tools that are able, already in a preliminary design stage, to highlight how a sustainable design choice can create value for customers and stakeholders, generating market success in the long term.

The paper objective is to propose a framework where Sustainable Product Development (SPD) and Value Driven Design (VDD) can be integrated to realize a model-driven approach to support early stage design decisions. Also, the paper discusses how methods and tools for Model-Based Decision Support (MBDS) (e.g., response surface methodology) can be used to increase the computational efficiency of sustainability- and value-based analysis of design concepts.

The paper proposes a range of activities to guide a model-based evaluation of sustainability consequences in design, showing also that capabilities already exist for combining research efforts into a multi disciplinary decision making environment.

**Keywords:** Sustainability, Design engineering, Conceptual design, Design process, Early design phases

### Contact:

Prof. Marco Bertoni  
Blekinge Institute of Technology  
School of Engineering  
Sweden  
marco.bertoni@bth.se

Please cite this paper as:

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

## 1 INTRODUCTION

In an industry such as aerospace, which features the introduction of advanced technologies with long life cycles, it does not come with surprise to see sustainability listed as one of the most significant drivers (ACARE, 2011)(ICAO, 2010) for the development of next generation air transport solutions.

While Systems Engineering practices (INCOSE, 2011) have been exercised for years to turn high-level design objectives into concrete targets on system functionality (e.g., lighter weight, noise reduction, emission reduction and high reliability), it is hard to decompose and clarify “sustainability” implications in the same way (Kaebernick et al., 2003; Pujari et al., 2004; Waage, 2007) and to trade-off sustainability against concrete targets on system functionalities and performances (Hallstedt et al., 2013, Bertoni et al., 2014).

While some aspects of sustainability are partially encompassed by the established drivers for design (e.g., specific fuel consumption, lifetime and weight reduction in the automotive and aerospace industry), others are less readily quantifiable (e.g. material criticality from an availability and socio-ecological sustainability perspective) and problematic to use as drivers for development.

It is evident that sustainability and value contribution are important aspects to include in design decisions. The difficulty of assessing and communicating ‘sustainability’ to technology developers is mainly due to the problem of showing numbers and ‘hard facts’ related to the value generated by sustainability-oriented decisions. The answer lies in methods and tools that are able, already in a preliminary design stage, to balance sustainability requirements with economic interests, highlighting how a sustainable design choice can create value for customers and stakeholders, hence generate market success in the long term. Overlooking the role of sustainability as a value-creating factor for the manufacturing industry increases business risk, and may result in expensive and time-consuming re-design efforts later in the product lifecycle.

## 2 MOTIVATION AND OBJECTIVES

Making engineering design decisions is a multi disciplinary task, where results and insights of different characters are traded against each other. Hence, engineering teams are used to model problems and generate from them the necessary information for decisions to be taken. The ability to apply a model-based thinking in the sustainability field is therefore critical for successful decision-making.

This paper addresses one such situation, where value and sustainability factors need to be judged in a context where more established engineering tools are used. Here, Value Driven Design (VDD) (Collopy and Hollingsworth, 2011) is seen as a promising area from which to derive models to support the identification of win-win-win situations, where sustainable improvements are aligned with business advantages (Hallstedt et al., 2013). VDD research, however, neither considers sustainability explicitly, nor proposes how value “models” can be applied to understand seemingly inconsistent, ill-defined and immature design situations, which are typical of the earliest stages of the design process.

With the purpose of bringing the important, yet high level and complex, aspects of “sustainability” into current engineering practices, the paper objective is to propose a framework where Sustainable Product Development (SPD) and VDD can be integrated to realize a model-driven approach to support early stage design decisions. Also, the paper discusses how methods and tools for Model-Based Decision Support (MBDS) (e.g., response surface methodology or surrogate modelling) can be used to increase the computational efficiency of sustainability- and value-based analysis of design concepts.

After discussing the model-driven challenge from a generic product development perspective, the paper details SPD, VDD and MBDS, placing them in the context of the knowledge value stream and product value stream representation proposed by Kennedy et al. (2008). The latter is used as a basis for proposing a framework where a range of activities is suggested to guide a model-based evaluation of sustainability consequences in product design. Eventually, the paper discusses how these 3 complementary scientific disciplines can be merged to build a multi disciplinary capability for engineering design teams.

### **3 METHOD**

The paper reports from an on-going 6-year initiative conducted in collaboration with a major aero-engine sub-system supplier. Research is conducted following an iterative process involving researchers and practitioners working together on a particular cycle of activities, including problem diagnosis, action intervention and reflective learning, in a similar way as described by Avison (1999) and Coughlan and Coughlan (2009). It involves a spiral of look-think-act routines (or “learning circles”) in which researchers test a theory with practitioners in real situations, gain feedback from this experience, modify the theory as a result of this feedback, then try again. Lessons learned are grown from several case studies (Yin, 2009), where empirical data are collected through regular (bi-monthly) multi-day physical co-creation workshops, and through semi-structured interviews with managers, engineers and information technology experts involved in the development of hardware and services related to aerospace products. Data gathering activities also benefit from the part-time physical presence of one of the researchers at the industrial facilities.

Reflective learning is aided by the continuous participation in regular debriefing activities, which takes the form of regular (bi-weekly) virtual meetings. The findings are iteratively discussed and validated with the project partners, in focus groups with industrial practitioners. Both qualitative (questionnaire) and quantitative data are gathered from such sessions. Compiling visual representations and demonstrators of the emerging modeling concepts is also an important means to validate techniques with company stakeholders and to identify critical topics for modeling.

### **4 NEEDS FOR DECISION SUPPORT IN THE PRODUCT INNOVATION PROCESS**

Over many decades, manufacturers of advanced technical products have developed skills, methods, tools and routines for decision support that are centred on performance and safety dimensions. Advancements made in the area of computational software for performance analysis (e.g., Computational Fluid Dynamics or Multibody Dynamics) and knowledge based approaches (e.g., Rule-based simulations and Knowledge Based Engineering) have significantly improved the quality of design studies by automating routine tasks.

The evolution of mechanical and knowledge engineering models is important, and for several disciplines tools and roles are already mature and established. Still, there is a need for a broader view on how models may be used to support not only the design of the technical hardware, but also the entire system of products and services. For decades, theories and developments have been shown to facilitate the integration of disciplines. In the domain of Product Service Systems (Mont et al., 2002; Baines et al., 2007), for instance, methods for virtual verification and multidisciplinary simulation have been proposed to take into account the complete product life cycle including disassembly and remanufacturing (Östlin et al., 2008).

Furthermore, as products have matured, and competitive pressure increases, new aspects become influential on decisions made during product development. Companies investigate more closely how to satisfy customer expectations to deliver “tacit” value aspects, such as ‘user comfort’, in an attempt to differentiate their offer from the competitors. While for business-to-consumer companies this step might seem self-evident, it is more surprising to see companies in the business-to-business sector, at different levels of the supply chain, looking at user and stakeholder value when designing sub-systems or components (Isaksson et al., 2013)(Bertoni et al., 2013). A second major factor gaining importance is the global challenges collectively addressed under the sustainability umbrella. From an engineering design perspective, both “Value” and “Sustainability” aspects are not yet made available as model based disciplines – equivalent to the exemplified disciplines above. There are several explanations to this:

- Both “Value” and “Sustainability” contain and present a significant portion of tacit concepts; “value” is generically defined as “perceived satisfaction of stakeholder needs”, while “sustainability” is even more complex in its definition, which is rooted in a list of principles (Holmberg and Robèrt, 2000).
- Analysis models and tools in this domain are less developed – at least as seen from a computational modeling perspective. Engineering design teams are today consistently refining their decision support systems with computational simulation tools in other areas.

- Data to populate and evaluate “value” and “sustainability” reside not only within the product definition, but also within its life cycle and usage context. Precision is typically low in early phases compared to readily available "hard targets" on physical performances, etc.

#### **4.1 Sustainability in the product innovation process**

Strategic sustainable development means to successfully do business in a way that contributes to an ecologically and socially sustainable society. This requires an understanding of what sustainability is, as well as a systematic approach to find challenges and opportunities to prioritize actions into a strategic plan for the transition. Sustainability issues in product innovation must also be considered in a life cycle perspective, looking at materials and chemicals used, at the manufacturing processes at the working environment in the manufacturing sites, at incentives for recycling and closed-loops business models within the value-chain.

Different support tools and methods, both of qualitative and quantitative nature, are needed when integrating and implementing a strategic sustainability perspective in the early innovation processes. Uncertainty on the data makes it difficult to measure consequences quantitatively, reducing the transparency of the decision. In parallel with the level of design freedom (Ullman, 1997), the possibility to reduce the sustainability impact during a product life cycle decreases with time into the design process. This means that, in order to efficiently bring in a sustainability perspective and be able to make business advantages out of that, it should be included early into the design process. This is consistent with most product development literature in the general sense: in order to influence the life cycle performance of products, knowledge needs to be available and utilized early in the process (Pujari, 2006).

Companies need to understand the global changes that contribute to both risks and opportunities that their profitability depends upon (Broman et al., 2000; Johnston et al., 2007). They may or may not explicitly define success from a sustainability perspective, but it should be clear how they utilize awareness of sustainability aspects in their work (Boks, 2006; Johansson, 2002; Jorgensen et al., 2006, Deutz et al., 2010). In addition, they also need to know how to coordinate, combine and integrate tools, methods and initiatives in the overall decision-making process (Knight and Jenkins, 2009).

#### **4.2 Value-driven product development**

VDD aims to solve design trade-offs looking at how much customers “value” certain capabilities against each other. It proposes model-based enablers to identify the combination of attributes of a product that ultimately produces the best overall economic value in a lifecycle perspective. Several authors (Castagne et al., 2009; Curran et al., 2010; Cheung et al., 2012) have applied VDD to optimize system design in aerospace. 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 of the design instance, in form of a vector of attributes that mirrors the customer preferences or “value scale”. These attributes are assessed against an objective function, typically Net Present Value and Surplus Value models (Price et al., 2012), which give a scalar score to any set of attributes. If the current configuration has a better score than any previous attempt, it is considered the preferred configuration to date. At this point, the design team can accept the configuration as their product, or may try to produce an even better design by going around the cycle again.

VDD is of interest to avoid falling in the trap of focusing only on the nearest customer and targeting local optimal solutions. VDD can be exploited to spotlight those dimensions that add value from a more system-level perspective, where sustainability is one of them. Although promising, value models are data intensive, hence difficult to build in the early phases of design (Soban et al., 2012). This suggests, at least in the earliest phases of the design process, looking both at more qualitative approaches (Isaksson et al., 2013)(Bertoni et al., 2013) and to exploit computer base support to extrapolate relevant information from historical data as a means to populate the models.

#### **4.3 Model Based Decision Support in Product Development**

Model-based decision support is already applied to support many product development tasks in a wide array of manufacturing industries. Perhaps most notably, response surface models allow engineers to evaluate, compare, and even enhance design concepts by letting them perform design space

exploration and design optimization (Mukhopadhyay et al., 2013). These tasks are often carried out using models that provide a mapping between quantitative descriptions of the design concepts and the outcomes of simulated tests on the corresponding CAD models of the concepts. Methods for generating such response surfaces are contributed from computer science (machine learning) and statistics. There are a number of caveats which concern the applicability and validity of surrogate modeling techniques when value or sustainability aspects are considered during the early design stages: the existing surrogate modeling methods are designed to handle quantitative input and output data. Relevant qualitative value or sustainability aspects would have to be transformed into quantitative variables. During the transformation, information loss or distortion can occur and this could decrease the validity of the results obtained later through design space exploration or optimization (Domingos, 2012). Even if qualitative value and sustainability aspects are carefully and realistically compartmentalized into quantitative variables, it is challenging to generate models that can accurately balance these variables against traditional quantitative engineering data.

One of the most difficult problems in machine learning and inferential statistics is to generate robust and accurate models based on small samples of data points defined by a large number of features. When additional variables are introduced (for example, value and sustainability aspects) to complement the traditional engineering data, the problem becomes even harder to solve. Another relevant problem to consider in this context, is the comprehensibility of the generated surrogate models: traditional methods for generating response surfaces (for example, support vector machines, artificial neural networks, and curve fitting techniques) are essentially generating black-box models. These models are able to predict or estimate the outcome, or response, for input data, but the inner workings of the models are hidden or incomprehensible (Allahyari & Lavesson, 2011). As the complexity of the design concept data grows, the need for transparent and comprehensible models becomes increasingly important.

## 5 A FRAMEWORK FOR MODEL BASED DECISION SUPPORT FOR VALUE AND SUSTAINABILITY

Starting point for the development of the framework is the model proposed by Kennedy et al. (2008), who describe the innovation process at the company dividing it into two value streams: a knowledge value stream and a product value stream (Figure 1).

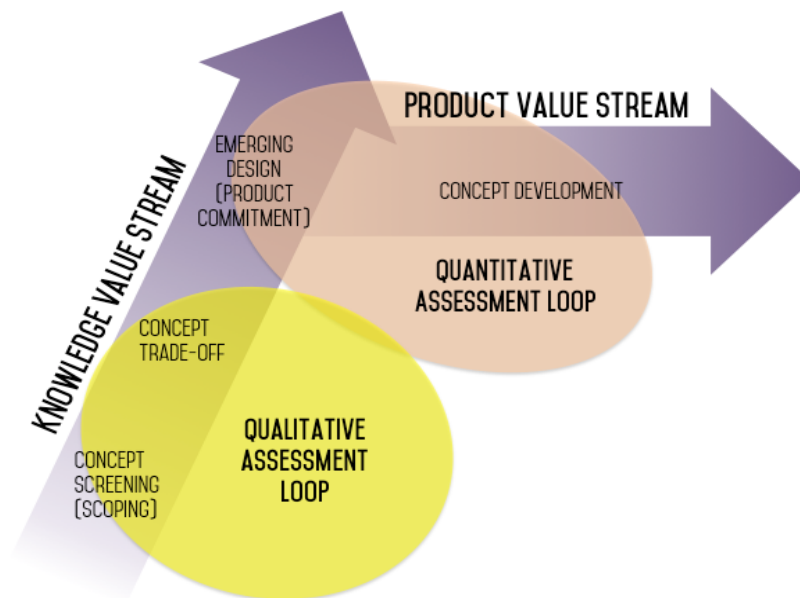


Figure 1. Knowledge vs. Product Value streams and their relation with qualitative- and quantitative assessment loops.

The first stream represents the capture and reuse of knowledge about markets, customers, technologies, products and manufacturing capabilities, which is general across projects and organizations. The latter 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. Looking at model-based approaches for sustainability assessment, the problem space touches both streams. It begins from the earliest phases of design, where the design problem is quite open. Here the alternative technologies to explore as solutions are many and there is a need to understand broadly the potential implications of ways forwards. The problem space further recognizes the conceptual design phases, where typically the engineering team has formulated concepts and begun modelling candidate solutions. Finally, the design space covers the more detailed phases of design, where the actual product and process are selected for detailing. Progressing along the two streams, different needs are observable when considering decision support, and the problem is that the “early phase” needs to be decomposed, as one method does not fit all.

- Scoping: decision support shall enable the screening of candidate solution strategies with limited effort and time, typically in the order of hours. Also, it shall enable the design team to handle situations where the information available is scarce, immature and incomplete.
- Emerging Design: decision support shall enable the design team to confine the design space and down select concepts from a range of possibilities. Iterations are executed within one or few days, and a first range of models for the design space is now available.
- Concept development: Any decision support in these phases shall enable a greater depth of analysis in the given contexts. Both product- and process definitions exist and are being refined to minimize risk, cost and any other requirements compliance necessary. The time frame for decision support tools is still time constrained; yet studies may now expand to weeks. Quality of data available increases, yet there is still not sufficient information to undertake complete LCA analyses as an example.

Figure 2 shows the framework proposed to facilitate the implementation of a model based decision support for value and sustainability in product development. It emphasizes two main assessment loops, a qualitative and a quantitative one.

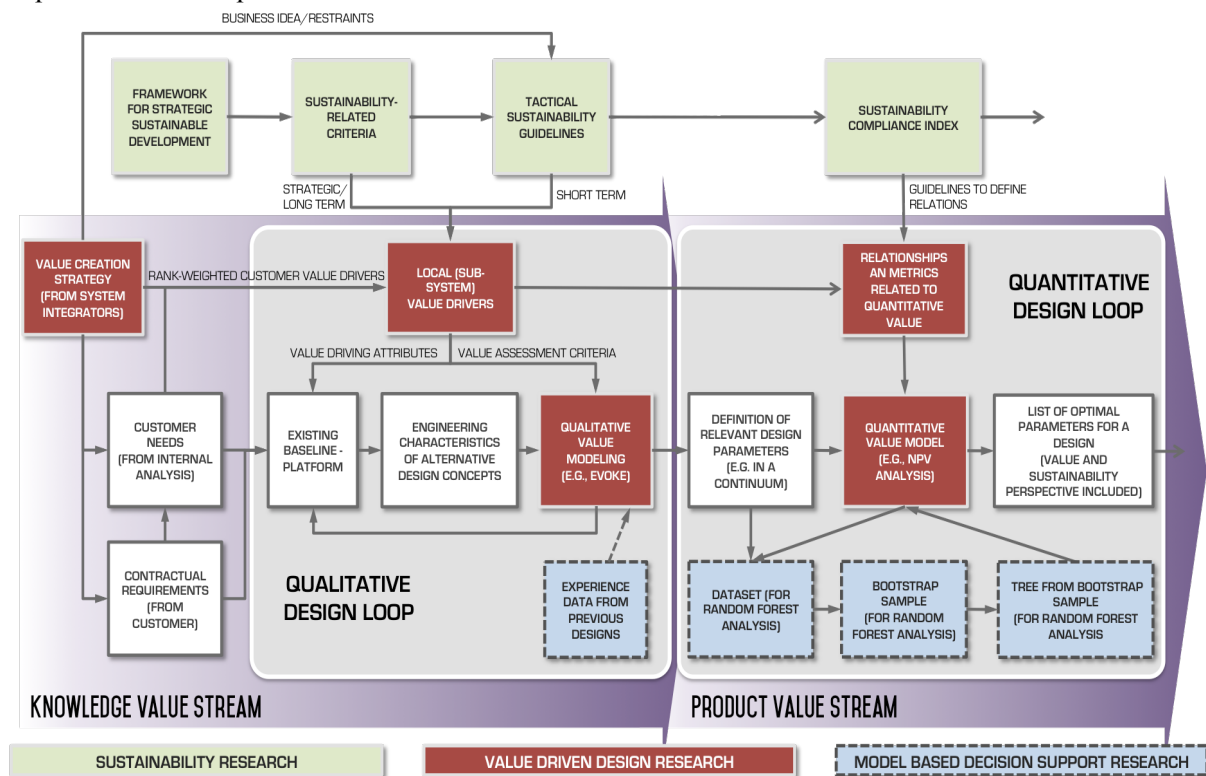


Figure 2. Schematic figure of an introductory approach for Model Based Decision Support for Value and Sustainability in Product Development

### 5.1 Qualitative assessment loop in the Knowledge Value stream

The Qualitative loop aims at generating a first assessment of the potential and risk associated to a design concept or technology, filtering potential technology candidates using a broader set of criteria than what happens today in preliminary design. Inputs to this loop are many and heterogeneous, in the

spirit of capturing the largest possible definition for value. Customer needs and contractual requirements are at this stage indicative at best, hence they need to be complemented by other descriptions, highlighting the overall intent of the design and the context in which requirements are generated. Context and design intent are considered crucial to raise awareness of the value creation opportunity embedded in different designs (Isaksson et al., 2013), and to eventually support decision-making in an early phase. Information on context and design intent emerges from long-term market/technology forecasts and from lessons learned earned in previous projects: it is formalized internally at the company in form of a list of customer needs. In addition, the Value Creation Strategy (in the form proposed by Isaksson et al., 2013) is used to communicate expectations and preferences from all the actors in the value chain, helping designers in further placing the received requirements in a context. Eventually, the Framework for Strategic Sustainable Development (FSSD) (Broman et al., 2000) broadens the understanding of the product to encompass environmental and societal needs. FSSD is detailed in guidelines, which are expressed as sustainability criteria (long term) and tactical guidelines (short term).

This heterogeneous set of information needs to be synthesized in homogeneous metrics so that benchmarking activities can take place. Value Drivers (VD) have been proposed as common denominator in this respect. As explained by Isaksson et al. (2013) and by Bertoni et al. (2013) VD are system characteristics less formalized and more volatile than requirements, but that carry contextual information on solution directions influencing the customer and end user value perception. VDs satisfy the independence condition, and features a n:n relationships with the dimensions and criteria expressed above. For instance, a need can be dissembled into many VD, while a VD can have an impact on one or more needs.

VD are the metrics by which different design alternatives are benchmarked. In aerospace these alternatives are seldom radically new designs, rather they often derived from the improvement of already known technology platforms. From the generic platform description, engineers gather information about the technical features of each design option under consideration. Based on its complexity, the solution can be divided into parts, whose Engineering Characteristics (EC) - such as material, size, weight, etc. - can be set independently.

By mapping the list of EC to the list of VD designers obtain a feedback on how “good” a design is for the selected value metrics. These mapping can be performed using different types of decision matrixes (i.e., qualitative value models), such as Pugh and Quality Function Deployment. Previous studies (Bertoni et al., 2013, Eres et al., 2014, Khamuknin et al., 2014) have applied the Concept Design Analysis (CODA) method, an extension of QFD proposed by Wooley et al. (2001), to generate such feedback. CODA is believed to better capture value (Eres et al., 2014) than traditional QFD, because it adopts non-linear relationships analogous to the Taguchi Loss Functions, which are believed to better approximate the customer response (VD) to changes in a technology attribute (EC) (Andersson and Sullivan, 1993). The result of CODA is a design Merit Score, expressed in % from 0% to 100%, where the latter represents the maximum amount of value that can be achieved by a design. With many EC and VD, populating the matrix-based value model easily becomes a lengthy and cumbersome work: knowledge has to be grown at each EC/VD intersection to understand how each relationship and function should be set. Machine learning algorithms are then proposed to support the process of populating the value model at this stage, extracting trends and relations from existing historical data, as well as projection data.

## **5.2 Quantitative assessment loop in the Product Value stream**

The Quantitative loop is triggered by the selection of a product concept from the pot of available technologies. It looks closer into the customer operational process, and has the purpose to evaluate how alternative product designs (which specify a selected technology) generate value during their lifecycle. This loop is conducted by focusing the analysis on the identification and evaluation of “sustainability hotspots” along the entire product lifecycle. The identification of such hotspots is conducted emerging from methods and tools proposed in the sustainability research. Environmental Impact Analysis (EIA), Strategic Sustainability Assessment (SSA) and the Sustainability Compliance Index (SCI) are some of the tools proposed and implemented for hotspot identification (Hallstedt et al., 2013; Bertoni et al., 2014). Bertoni et al. (2014) shows the use of the above tools to identify the sustainability hotspot for an aero-engine component. Looking at the product lifecycle, the manufacturing process was highlighted as a potential hotspot. Statements from the EIA showed that

the Electro-Chemical Milling (ECM) processes, featured by one of the chosen product options, was responsible to generate hexavalent chromium Cr(VI), an highly toxic compound. SSA further clarified the risks of investing in ECM, pointing towards the use of Mechanical Machining (MM) as replacement. To better understand the monetary consequences of selecting an MM-manufactured component compared to an ECM one, a quantitative value model was used. The model featured an NPV analysis based on a 10 year period, which was conducted under different assumption (i.e., scenarios) for what concerns the introduction of more stringent laws and regulations related to the management of ECM and its waste.

Response surface methodology or surrogate modelling can be used at this step to increase the computational efficiency of the simulation-based analysis. In this respect, experiments have been conducted (Dasari et al., 2014) to compare the performance of tree models (M5P and random forests) with the performance of non-tree models (support vector machines and linear regression) on data that is typical for design concept evaluation within the aerospace industry. The main finding indicates that comprehensible models (the tree models) perform at least as well as, or better than, traditional black-box models (the non-tree models).

## **6 DISCUSSION AND CONCLUSIONS**

The overall aim of this research is to form a framework for developing model-based decision support based on three key research domains needed to co-create solutions.

The results to date show that both the necessary conditions and state of the art capabilities exist for combining research efforts into a multi disciplinary decision making environment, if a common problem context is given. In particular, the authors believe that bridging qualitative and quantitative aspects into a model based decision environment is achievable, both from an academic and an applied perspective, with existing methods and tools.

On a broader, multi-disciplinary level, the authors have identified a set of key challenges that must be addressed for the proposed framework to be successfully implemented in the day-to-day engineering work. Firstly, the research community needs to establish robust design criteria for product development, extending the existing model-driven development approaches to support multi-disciplinary and multi-criteria decision-making. Then, these criteria must be coupled with methods for visualising value and sustainability-related information in the context of (or in relation with) traditional engineering data.

A main lesson learned in the process of creating the proposed framework is related to the strategy that should be followed by the research team to address these challenges. What the authors propose is to introduce unity by focusing on a small set of real-world scenarios, and to introduce diversity by performing parallel studies of the scenarios using different perspectives and expertise from a variety of relevant disciplines. These parallel studies contribute to (what can be considered as) a holistic approach for establishing the model-based decision support framework.

There are arguments for and against model-based decision support for value and sustainability in product development. Examples of arguments for a model-based decision support are:

- Engineering teams are used to model problems and use modeling results for decision making such as FEA and CFD modeling for stress and fluid flow performance.
- Quantification of aspects is driven by a modeling approach, and once quantified the search for (and evaluation of) solutions is made simpler.
- Modeling that formalizes both "fuzzy" aspects enable them to be linked to design features on quite detailed level of solutions (e.g., linking sustainability impact with engineering characteristics of a product or a process).
- Modeling enables visualization and facilitates understanding in design teams.

Examples of arguments against a model-based decision support for value and sustainability in product development are:

- Value and sustainability issues are multi-faceted, often context dependent and difficult to condense into a unified way of modeling. "Sustainability Data" is difficult to validate in manageable experiments and is rarely available in today's requirements for product development.
- Quantification may drive reductionism, and lead to sub-optimization.



- Aggregation of detailed design information via models may give a false impression of precision.
- Modeling may hide important aspects and figures replacing “wiseness” is seldom successful.

Finally, already a first set of collaborative research studies has been undertaken as identified in the framework with promising result. High potential and novel combinations of research, combining e.g. value and sustainability with computer science governed techniques has also started, whereas there is a somewhat longer time until mature effects can be reported.

## ACKNOWLEDGMENTS

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

## REFERENCES

- ACARE (2011) Flighthpath 2050 – Europe’s Vision for Aviation. Report of the High Level Group on Aviation Research. Advisory Council for Aeronautics Research in Europe, October 2004. Publications Office of the European Union. ISBN 978-92-79-19724-6.
- Allahyari, H. and Lavesson, L. (2011) User-oriented Assessment of Classification Model Understandability, 11th Scandinavian Conference on Artificial Intelligence, Trondheim, 24-26 May, pp. 11-19.
- Anderson, E.W. and Sullivan, M.W. (1993) The antecedents and consequences of customer satisfaction for Firms. *Marketing Science*, Vol. 12, pp. 125-143.
- Avison, D., Lau F., Myers M. and Nielsen P.A. (1999) Action Research. *Communications of the ACM*, Vol. 42, No. 1, pp. 94–97.
- Baines, T.S., Lightfoot, H.W., Evans, S., Neely, A., Greenough, R., Peppard, J., Roy, R., Shehab, E., Braganza, A., Tiwari, A., Alcock, J.R., Angus, J.P., Bastl, M., Cousens, A., Irving, P., Johnson, M., Kingston, J., Lockett, H., Martinez, V., and Michele, P. (2007) State-of-the-Art in Product-Service Systems. *Journal of Engineering Manufacture*, Vol. 221, No. 10, pp. 1543-1552.
- Bertoni, M., Bertoni, A. and Isaksson O., Amnell, H. and Johansson, C. (2013) Value-oriented concept selection in aero-engine sub-systems design: the EVOKE approach. 23<sup>rd</sup> annual INCOSE International Symposium, Philadelphia (PA), 24-27 June.
- Bertoni, M., Hallstedt, S., Isaksson, O. (2014) Value assessment of sustainability hotspots in conceptual design: an aerospace study. *Tools and Methods for competitive engineering (TMCE)*, Budapest, Hungary, 19-23 May.
- Boks, C. (2006) The soft side of ecodesign. *Journal of Cleaner Production*, Vol. 14, No. 15-16, pp. 1346-1356.
- Broman, G., Holmberg, J. and Robèrt, K.-H. (2000) Simplicity Without Reduction: Thinking Upstream Towards the Sustainable Society. *Interfaces*, Vol. 30, No. 3, pp. 13-25.
- Castagne, S., Curran, R., and Collopy, P. (2009) Implementation of Value-Driven Optimisation for the Design of Aircraft Fuselage Panels. *International Journal of Production Economics*, Vol. 117, No. 2, pp. 381-388.
- Cheung, J., Scanlan, J., Wong, J., Forrester, J., Eres, H., Collopy, P., Hollingsworth, P., Wiseall, S. and Briceno, S. (2012) Application of Value-Driven Design to Commercial Aero-Engine Systems. *Journal of Aircraft*, Vol. 49, pp. 688-702.
- Collopy, P. and Hollingsworth, P. (2009) Value-Driven Design. In *Proc. of the AIAA Aircraft Operations Technical Committee*, Hilton Head, SC.
- Coughlan, P. and Coughlan, D. (2009) Action Research. In: Karlsson, C. (ed.). *Researching Operations Management*. 1st ed. New York: Routledge.
- Curran, R., van der Zwan F.M., Ouwehand, A. and Ghijs, S. (2010) Value Analysis of Engine Maintenance Scheduling Relative to Fuel Burn and Minimal Operating Costs. *American Institute of Aeronautics and Astronautics*, Reston, VA, Paper 2010-9145.
- Dasari, S.K., Lavesson, N., Andersson, P., Persson, M. (2015) Tree-Based Response Surface Analysis. Submitted to *International Workshop on Machine learning, Optimization and big Data (MOD 2015)*, Taormina, Italy, 21-24 July.
- Deutz, P., Neighbour, G., and Mcguire, M. (2010) Integrating Sustainable Waste Management into Product Design: Sustainability as a Functional Requirement. *Sustainable Development*, Vol. 18, pp. 229-239.
- Domingos, D. (2012) A few useful things to know about machine learning. *Communications of the ACM*, Vol. 55, No. 10, pp. 78-87.
- Eres, M.H., Bertoni, M., Kossmann, M., and Scanlan, J.P. (2014) Mapping customer needs to engineering characteristics: an aerospace perspective for conceptual design. *Journal of Engineering Design*, Vol. 25, No. 1-3, pp. 64-87.

- Hallstedt, S., Thompson, A. and Lindahl, P. (2013) Key Elements for Implementing a Strategic Sustainability Perspective in the Product Innovation Process. *Journal of Cleaner Production*, Vol. 51, No. 15, pp. 277–288.
- Holmberg, J. and Robèrt, K.-H. (2000) Backcasting - a framework for strategic planning. *International Journal of Sustainable Development and World Ecology*, Vol. 7, No.4, pp. 291-308.
- INCOSE (2011) *Systems engineering handbook v3.2.2*, International Council on Systems Engineering.
- International Civil Aviation Organization (2010) ICAO Environmental Report 2010. Available at: [http://www.icao.int/environmental-protection/Documents/Publications/ENV\\_Report\\_2010.pdf](http://www.icao.int/environmental-protection/Documents/Publications/ENV_Report_2010.pdf)
- Isaksson, O., Kossmann, M., Bertoni, M., Eres, H., Monceaux, A., Bertoni, A., Wiseall, S. and Zhang, X. (2013) Value-driven design - a methodology to link expectations to technical requirements in the extended enterprise. 23<sup>rd</sup> annual INCOSE International Symposium, Philadelphia (PA), 24-27 June.
- Johansson, G. (2002) Success Factors for Integration of Ecodesign in Product Development: A Review of State-of-the-art. *Environmental Management and Health*, Vol. 13, No. 1, pp. 98-107.
- Johnston, P., Everard, M., Santillo, D., and Robèrt, K.-H. (2007) Reclaiming the definition of sustainability. *Environmental Science and Pollution Research*, Vol. 14, No. 1, pp. 60-66.
- Jorgensen, T., Remmen, A. and Mellado, M. (2006) Integrated management systems – three different levels of integration. *Journal of Cleaner Production*, Vol. 14, No. 8, pp. 713-722.
- Kaebnick, H., Kara, S. and Sun, M. (2003) Sustainable product development and manufacturing by considering environmental requirements. *Robotics and Computer Integrated Manufacturing*, Vol. 19, pp. 461–468.
- Kennedy, M., Harmon, K. and Minnock, E. (2008) *Ready, set, dominate - Implement Toyota's Set-Based Learning for Developing Products and Nobody Can Catch You*. Richmond: The Oaklea Press.
- Khamuknin, A.A., Bertoni, M. and Eres, M.H. (2015) Avoiding Resonant Frequencies in a Pipeline Application by Utilising the Concept Design Analysis Method. *International Conference on Engineering Design*, Milan, 27-30 July.
- Knight, P., and Jenkins, J.O. (2009) Adopting and applying eco-design techniques: a practitioners perspective. *Journal of Cleaner Production*, Vol. 17, No. 5, pp. 549–558.
- Mont, O. (2002) Clarifying the concept of product-service system. *Journal of Cleaner Production*, Vol. 10, pp. 237-245.
- Mukhopadhyay, T., Chowdhury, R. and Chakrabarti, A. (2013) Reliability analysis of response surface based damage identification method. *Scientific & Engineering Research*, Vol. 4, No. 5, pp. 220-223.
- Ny, H., MacDonald, J.P., Broman, G., Yamamoto, R., Robèrt, K.-H. (2006) Sustainability constraints as system boundaries: an approach to making life-cycle management strategic. *Journal of Industrial Ecology*, Vol. 10, No. 1-2, pp. 61-77.
- Östlin, J., Sundin, E. and Björkman, M. (2008) Business Drivers for Remanufacturing. 15th CIRP International Conference on Life Cycle Engineering, Sydney, 17-18 March.
- Price, M., Soban, D., Mullan, C., Butterfield, J. and Murphy, A. (2012) A novel method to enable trade-offs across the whole product life of an aircraft using value driven design. *Journal of Aerospace Operations*, Vol. 1, pp. 359–375.
- Pujari, D. (2006) Eco-innovation and new product development: understanding the influences on market performance. *Technovation*, Vol. 26, pp. 76–85.
- Pujari, D., Peattie, K. and Wright G. (2004) Organizational antecedents of environmental responsiveness in industrial new product development. *Industrial Marketing Management*, Vol. 33, No. 5, pp. 381-391.
- Soban, D.S., Price, M.E., and Hollingsworth, P. (2012) Defining a Research Agenda in Value Driven Design: Questions That Need to be Asked. *Journal of Aerospace Operations*, Vol. 1, No. 4, pp. 329-342.
- Ullman, D.G. (1997) *The Mechanical Design Process* (2nd ed.). New York, NY:McGraw-Hill.
- Waage, S.A. (2007) Re-considering product design: a practical ‘‘road-map’’ for integration of sustainability issues. *Journal of Cleaner Production*, Vol. 15, pp. 638-649.
- Woolley, M., Scanlan, J.P. and Eveson, W. (2001) Optimising the development of a medical device using formal engineering design techniques and the coda-system. 7th International Conference on Concurrent Engineering, Bremen, Germany, Vol. 201, pp. 26-29.
- Yin, R.K. (2009) *Case Study Research: Design and Methods*. (5th ed.). Thousands Oaks, CA:Sage.