Experiences with value visualisation in preliminary design: results from an aero-engine component study

M. Bertoni¹, A. Bertoni¹, O. Isaksson²
¹Division of Innovation and Design, Luleå University of Technology, 97187, Luleå, Sweden
marco.bertoni@ltu.se, alessandro.bertoni@ltu.se
²PD Quality Volvo Aero Corporation, SE-461 81 Trollhättan, Sweden.
ola.isaksson@volvo.com

Abstract
Value is an appealing concept to elaborate a concise, over-arching cross-system requirements specification to support the preliminary design phase of an aerospace development project. The paper aims to address the lack of intuitive visualisation means for communicating ‘value’ during preliminary design tasks by proposing an approach that uses colour-coded 3D CAD models. The methodological and technological enablers for value visualisation have been tested in design sessions with undergraduate students, showing that they stimulate the analysis of the value assessment report and the discussion on value-related matters.

Keywords:
Conceptual design, Value driven design, Information visualisation, colour-coding

1 INTRODUCTION
Conceptual Design is considered the most important phase of the design process [1], because the decisions made here will have a strong impact on all subsequent phases of design. A weak concept can never be turned into an optimum detailed design [2]. Design decisions are associated with consequences [3], which can either be intended or unintended and either good or problematic, and have the ability to influence the performance of other life-cycle phases in terms of measures such as cost and time [4]. Hence designers need to be aware of the consequences of the decisions made during conceptual design [3] on the whole context of the design problem under consideration, which is the external world, life phases, environment of the product and users of the product [2].

In the aerospace industry concept development is also a highly collaborative activity, involving many individuals from a large variety of suppliers and sub-contractors, which uses product requirements as main reference for all design choices. However, providing requirements specification fully encompassing project intent and brand identity is not an easy issue. Requirements alone, in fact, cause insufficient insight into the original intent and context of a design, increasing the risk of delay, rework and sub-optimal solutions.

In such a situation, it is crucial to provide to the supply chain partners adequate information, clarifying the context and underlying intent of each requirement. The lacking of a holistic view and of a flexible approach to develop attractive solutions, might lead to sub-optimisation - suppliers have a tendency to follow their “normal specification” and make decisions in line with their own preferences [5] - or even to project stagnation.

The concept of ‘value’ becomes then appealing for aircraft and aero-engine manufacturers to elaborate a concise, over-arching cross-system requirements specification providing a summary of most important requirements. Value provides a means to formalise such contextual information in a more structured form, taking relevant chunks out of the requirement specification and dispatching them to concerned sub-suppliers [5]. This increases designers’ awareness of the consequence of their choices during the design synthesis stage, when decision-making takes place.

2 MOTIVATION AND OBJECTIVES
Empirical evidence suggests that current Systems Engineering standards do not address ‘value’ in much detail. In spite of designers being recognised as “visual thinkers” [6] the authors have observed that there is a little use of intuitive visualisation means for communicating ‘value’ during preliminary design tasks. Hence value visualisation strategies and techniques are needed to ensure that the added value of a design is fully understood in the process of developing and managing large technical systems.

The paper investigates how to represent the value contribution of alternative sub-system technologies during preliminary design, as a means to guide value trade-offs at the decision gate. The objective is to present the findings from the empirical study related to:
• the engineering need for visualising value information during preliminary design concept selection;
• the methodological and technological enablers (colour-coded 3D CAD models) for value visualisation;
• the results of testing activities conducted on the colour-coded models on design sessions with undergraduate students.

The paper exemplifies the use of these approaches using as a reference an aero-engine component.

3 METHODOLOGY
The findings – i.e., the methodological and technological enablers - have emerged from the analysis of real industrial problems within the European Commission’s FP7 CRESCENDO project (http://www.crescendo-fp7.eu/) between May 2009 and June 2012. The definition and clarification of the problem domain have been conducted mainly through the authors’ active participation in physical work-meetings within the project. Several multi-day physical workshops have been held with major European companies with experience in aircraft and aero-engine development programmes, involving more than 35 people from 12 different partners (i.e., aircrafts, engines and sub-systems manufacturers, universities and software vendors).

The problem has been detailed in collaboration with a major Swedish aircraft sub-system manufacturer. Data about decision makers’ and system users’ needs have been collected during multi-day company visits at the industrial partner’s facilities. Semi-structured interviews and focus groups [7] have been used as main data collection methods. The data gathering activity has involved managers, engineers and IT experts with knowledge on product and service development processes.

Reflective learning has been aided by the continuous participation in regular debriefing activities, which have taken the form of weekly virtual meetings with a range of product development experts, who have participated with their knowledge and expertise to the development of a preliminary mock-up for value visualisation.

Validation has been performed both in industry and academia. Multi-day project review meetings have been held with stakeholders from a wide range of major European aeronautical companies. Laboratory experiments have been conducted with master students, featuring design sessions analysed by means of protocol analysis and questionnaires.

4 BACKGROUND
Modern aircraft development programmes, such as the Airbus A350 XWB (eXtra Wide Body), feature a number of work packages contracted to risk sharing partners, which are further sub-contracted to a large variety of other suppliers and sub-contractors. Outsourcing might facilitate better utilisation of suppliers’ competences, implying shared development cost and risks.

Contractual (technical) requirements represent the main reference for any work in such partnerships. Requirements are signed off between directly interfacing partners, ensuring robustness and quality of the development process outcome. Throughout the development of a new aero-engine, for instance, thousands of requirements are established, communicated, transformed into solutions, followed up, and verified.

To reduce development cycles and time-to-market, companies dealing with long lead-time items (such as engine components or landing gears) have to start working long before mature requirements are made available to them by the Original Equipment Manufacturer. Even if available, in an early stage they are often incomplete, conflicting and subject of later changes. During their long period of gestation, requirements are changed, prioritised, compromised, balanced as the product development team gain experience and insight [8], and late discovered product requirements are fairly common [9]. As a consequence, the result of development activities at sub-system level does not always mirror the driving factors for the project, and is then most likely to be regarded as less successful than what was originally expected.

Support is needed in an early phase to allow the comparison of radically different concepts with incomplete information, encompassing both “technical” and “in-service” (e.g., availability, predictability, reliability) aspects. In aerospace projects ‘value’ is then used to cope with these issues. Value is seen as a way to provide punctual and actionable criteria to enable early design “what-if” analysis to be executed against different product/service alternatives, thus being able in an early phase to evaluate the “goodness” of a concept for the overall system.

The Value Driven Design literature provides several examples of how to complement current engineering practices with value-related approaches.

Profitability is by far the most intuitive dimension to assess the value of a system. Value Driven Design (VDD) (http://www.vddl.org/vdd-home.htm) represents a major effort toward the introduction of economic principles in the engineering decision making process. VDD propagates the long-term profitability idea to systems and sub-systems, enabling optimum solution strategies to be instantiated in an objective, repeatable, and transparent manner. A “value model” in VDD is a function that accepts as argument a vector of attributes, to assign a score (scalar) to rank a design. This score is called Surplus Value and is a surrogate object for profit. It takes the form of Net Present Value (NPV), which represents an unbiased metric on the ‘goodness’ of the final product [10].

For systems characterised by high costs, long lifecycles, high complexity, interdependencies with other systems and dynamic operational contexts,
value is also determined by the ability to maintain or improve systems functions in the presence of changes. The Epoch framework [11] 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", under changing process conditions. Real options for flexibility [12] and Value-Centric Design [13] put also the emphasis on quantifying the value of flexibility and robustness.

Value is also closely connected with uncertainty, as the value perceived for a certain solution changes depending on the changing environment. In this field, Briceno and Mavris [14] proposed a method to determine the value of design under market uncertainties by the use of game theory and NPV evaluation. Cardin et al. [15] further elaborated on uncertainty, using Monte Carlo simulation and financial functions such as Return on Assets (ROA), NPV or Value At Risk and Gain (VARG) to help designers and managers of engineering systems in incorporating flexibility at an early design stage.

Steiner and Harmor [16] proposed an extended model of customer value, adding a new layer: intangibles. Goods and services, in fact, can be arrayed on a continuum of relative tangibility, with goods being more tangible and services more intangible. Intangibles are associated with knowledge, emotion, and experience, dimensions that cannot be experienced by the customer before using the product (such as epistemic emotional or image value). Intangibles can interact with the product layer and the service layer to form a "value platform" from which total customer value is some combination of each layer of the total product.

In the end, the value of a system is likely to be found at the intersection of all the dimensions presented above. Using only one dimension might be misleading, as none of them, if taken stand-alone, can provide a satisfying picture of what the system value is in the real life. The system might be too complex to analyse, knowledge might be lacking, and numbers might not be mature enough to be trusted.

5 CHALLENGES IN VALUE VISUALISATION FOR CONCEPT SELECTION

Information and knowledge visualisation have been recognised as key factors to leverage the way value-related information is used in conjunction with requirements during early concept selection activities. More value robust decisions require enhanced means for communicating value contribution and design intent in terms that are immediately meaningful to engineers.

5.1 Information visualisation for decision making and concept selection

A number of scholars have empirically studied the dynamics of decision-making meetings, observing that information visualisation increases individuals' ability to perform some cognitive activities, such as knowledge discovery, explanation and decision making [17]. Visual representation results in greater decision-making accuracy, as it facilitates the direct examination of the complex relationships in the data [18]. Fishburn et al. [19] indicates that groups supported by extensive visualisation achieve higher productivity, higher quality of outcomes, and greater knowledge gains, hence better team performances. Computer-supported, interactive, visual representations of data amplify cognition and generate various benefits, such as: increasing the memory and processing resources available to the user, enabling perceptual inference operations and enhancing the detection of patterns [17].

Visual representations improve the creation and transfer of knowledge between people, by sharing what they know and what they need to know through perspective making and sharing. Visualisation is of particular importance, therefore, in all those design situations that require the ability to elicit and visualise personal and shared knowledge structures of different communities [20], such as in the cross-functional development teams featured in aerospace development projects.

5.2 Influence of colours for decision making

Information overload is a major problem in decision making [21]. Decision makers need to avoid the risk of neglecting relevant aspects while receiving a continuous stream of information that needs to be filtered by relevance. The theory of cue-summation [22] proposes the use of multiple cues to enhance associative processing and mitigate information overload. Studies have highlighted the importance of colours as supplementary information cues in interface designs [23]. Colours have been found to be the most effective coding technique for aiding visual searches [24][25], improving the usefulness of an information display system [26].

As colour is a basic element of visual perception, the processing of colour precedes the processing of other attributes [27] and does not require large amounts of cognitive capacities [28]. Experiments conducted by Benbasat [29] indicate that subjects with colour-coded reports obtain a significantly higher average profit over the first 10 trials and complete tasks using fewer trials. As the colour of objects is stored in long-term memory together with other object information (e.g., [30]), information on the colour of an object provides an additional cue for memory retrieval and fosters learning [31]. It can be hypothesised then, that information visualisation using a meaningful colour-coding should be superior to those without colour coding, as multiple memory traces should enhance learning [32].

In summary benefits and risks of information visualisation in decision-making activities have been largely treated in literature, and the influence of colour and graphical information presentation in a managerial environment has been discussed since the 1970s. Nevertheless the benefits of such approaches are nowadays scarcely captured in aerospace preliminary design, due to the limited availability of method and tools that integrates smoothly into the everyday design work.
6 VALUE VISUALISATION: FINDINGS FROM THE EMPIRICAL STUDY

The methodological and technological enablers for value visualisation have been developed, exemplified and tested in a case study related to the development of an aero-engine intermediate compressor case (IMC) technology. The IMC is the biggest static component in the aero-engine and plays a key role from both a structural and a functional perspective. A major ambition for the IMC manufacturer is to use value as a transparent and well-understood driver for preliminary product and service development. Nowadays high/low cycle fatigue, limit/ultimate load capability, hale ingestion, strength and stiffness, corrosion, oxidation and creeps are the main criteria used for the evaluation of IMC concepts at the gate. However, the overall goodness of the technology cannot be assessed only looking at these parameters. Other dimensions, such as scalability, flexibility or environmental impact need to be considered to make more value-robust choices. Furthermore, the IMC is part of engines provided in power-by-the-hour agreements, which means that the design has to be targeted towards a successful functional life.

In such a context, the need analysis has highlighted a set of critical aspects to be addressed when communicating the value of such technology. Firstly, value needs to be expressed in relative terms, on the basis of well-recognised benchmarks: a product baseline (such as the actual product performances) and a target (such as the specification of a vision emerging from long-term forecasts). Absolute figures, in fact, are characterised by too much uncertainty and are poorly reliable. Secondly, value information needs to be more closely related to the requirements description and to the product geometry/shape to make easier for engineers to elaborate on value aspects during trade-offs analysis. Thirdly, there is a need of extending economical criteria to encompass more intangible aspects (e.g., comfort, adaptability) in the evaluation, encompassing also service aspects.

The need analysis showed a set of preferences toward representing value information to cross-functional and cross-organisational design teams. Firstly, there is a need to express value contribution using a common denominator to enable comparison between heterogeneous value dimensions. Secondly, there is a need to highlight those value dimensions that are positively/negatively affected by new designs (compared to a product baseline). Engineers need to be able to recognise areas where to trade excellent value performances with areas where the value analysis outcomes are not satisfactory. Thirdly, there is a preference toward associating the value assessment results to the product geometry/shape and to the requirements description, to facilitate the recognition of “patterns of behaviour”.

7 VALUE VISUALISATION FOR DECISION SUPPORT

The authors have observed that, in spite of the interest towards enhancing CAD tools for the integrated representation of function, service activity and product behaviour [33], means are still lacking concerning the use of 3D models to convey usage, manufacturability and life cycle information [34]. PLM/CAD systems, in fact, are claimed not to properly support early design concept visualisation, as they require thinking at a level of quantitative detail that is usually irrelevant of even detrimental to early concept design [6]. However, 3D CAD models represent a good trade-off between perception of product representation and frequency of use when compared with other visualisation means (such as Prototypes, Mock-ups, or Virtual Reality) [9].

Emerging from these considerations, the authors have developed an approach that uses colour-coded 3D CAD models to translate the value analysis outcomes into visual features. Three-dimensional models increase the designer’s conceptual capacity, thus increasing the quality of the design [35] and can be easily shared over the Internet, increasing communication between customers and suppliers [35].

The choice has been also dictated by the evident difficulty of integrating visualisation tools in daily work practice of large companies (see [36]) Even if a new system may be designed to improve on conventional tools or techniques, experts are very accustomed to and effective with previous solutions. This effectiveness naturally leads to attachment to the traditional tool and results in reluctance to learn a new system [36]. Furthermore, large companies require the authorisation of software or software components upfront for reasons of functionality and security [36]. This process may require highly collaborative synchronisation efforts and may become long and exhausting.

Under these circumstances, CAD tools are then preferable, as they are well integrated to perform within a chain of other tools, so that they together provide more encompassing analysis solutions.

7.1 Translating the value analysis outcomes in colour-coded representations

In the case study, the IMC value contribution has been computed using the Customer Oriented Design Analysis (CODA) approach [37], which evolves from more traditional QFD techniques. CODA outputs a Design Merit score for a list of Value Drivers considered relevant for the study. Design Merit \((DM)\) is expressed in ‘percentages’ reflecting the degree of satisfaction of a given driver. The CODA outcomes are then mapped against a 9-point scoring system. The purpose is to transform value model results (from the CODA, but also from other suitable value models) into scalars by applying an algorithm that gets as input the value model results for a given option \((DM_1')\) for the baseline \((DM_0)\) and for the target \((DM)\). The value Score \((S)\) for the given option is computed using the formula:
\[
S_v = \frac{(S_b - S_v)(DM_v - DM_b)}{(DM_v - DM_b)} + S_b
\]  
where \((S_b)\) represents the value score for the baseline, which is a-priori set equal to 3, while \((S_v)\) represents the value score of the target, which is a-priori set equal to 8. It has to be noted that the formula is only applicable when:
\[
\frac{(7DM_b - 2DM_v)}{(S_b - S_v)} \leq DM_v \leq DM_b
\]

On the one hand, in case:
\[
DM_v > DM_b
\]
the algorithm automatically assigns a score of 9 to the design alternative. \(S_v=9\) denotes a design better in value compared to what was considered as the best desirable outcome for the forthcoming solution. On the other hand, in case:
\[
DM_v < \frac{(7DM_b - 2DM_v)}{(S_b - S_v)}
\]
the algorithm automatically assigns a score of 1. \(S_v=1\) denotes a design scoring significantly below the baseline. Four main areas are then identified.

\(S_v=1/2\) indicates NO-GO designs whose value contribution is below the baseline. Based on the criticality of the driver/dimension, this may cause the design to be definitively killed for not satisfying the minimum requirements set by the baseline; otherwise, if the criticality is low, engineers may decide to accept a lower value score if this allows for more important dimensions to be improved.

\(S_v=3/4\) indicates designs that meet the minimum threshold. This score might be considered satisfactory if the criticality is low and major improvements have been achieved in dimensions with higher priority. For more critical aspects, it may trigger the decision to kill the development process, especially when resources for rework activities are limited.

\(S_v=5/6/7\) indicates designs in the GO area, although attention has to be paid on the reliability of the value assessment results. The design is moving in the right direction, but some refinements may still be made to achieve the desired development process outcome.

\(S_v=8/9\) indicates designs showing a higher value than what was originally intended. Engineers at this point can further analyse the "over-the-target" dimension to trade-off such excellent capabilities with other value drivers that are performing poorly, being free to decrease the value of the first in order to increase the value of the latter.

The colour scale selected feature different colour nuances, ranging from red (lowest value contribution, \(S_v=1\)) to yellow (\(S_v=5\)) to dark green (highest value contribution, \(S_v=9\)) (see Figure 1). The use of basic colour has not been preferred, because they do not segregate “exceptionally well” [25] and because chromatic gradation within hue or colour category is more appropriate for similar specific applications [25].

### 7.2 Implementation in the CAD environment

SIEMENS NX is the environment where the colour-coded 3D models have been realised, using the HD3D visual reporting capabilities. Figure 1 shows an example of colour-coded IMC model for a relevant value driver (maintainability). In this example, the IMC has been broken down in 6 main building blocks (engine mounts, fan case, guide vanes, thrust lugs support, internal and external hub wall). Each block has been assessed from a value perspective using CODA. Comparing the results of the assessment with data obtained for the baseline and target design, each block has been colour-coded accordingly. Red and orange indicates parts where the value contribution is equal or below the baseline design. Green indicates a value contribution in line with the target. Yellow represent areas where the value contribution is above the baseline, but not yet satisfactory for the purpose of the project.

![Figure 1: Colour-coding implementation in SIEMENS NX HD3D environment.](image)

A major problem with value assessment is that, in a preliminary phase, the value models vary a lot in terms of quality and reliability. A way to support decisions makers is to display the maturity of the knowledge on which the value model is built. Knowledge Maturity [38] is displayed a complementary dimension for value. It is assessed over three dimensions - input, method (tool), and expertise (experience) - on a scale from 1 (lowest maturity) to 5 (highest maturity). Knowledge maturity has been associated to tags, which are displayed together with the colour-coded model.

### 8 VERIFICATION IN DESIGN SESSIONS

Verification activities have been initially conducted in industry to gather qualitative feedback from experts and practitioners about the usefulness of the approach.
The colour-coding concept was presented and discussed with the project partners, mainly involving three major European aerospace manufacturers together with IT solutions vendors. The approach has been acknowledged to enhance decision support system capabilities, by improving the mutual communication and understanding of value between the members of the cross-functional design team, as well as the perception of the impact on value of different design strategies. Value and knowledge maturity visualisation have also been acknowledged to stimulate the design team's participants in probing the underlying knowledge base. Individuals have started to objectify and find facts about the system value contribution, asking questions about the underlying data quality, which otherwise would not even be considered.

Furthermore, the authors have designed and conducted experiments using protocol analysis to analyse the designers' behaviour during design episodes. The experiments have featured design sessions with researchers and students from the master programme in product development. The objective was to measure the effectiveness of colour-coded CAD models as value carriers, by comparing them with other forms of visualisation, such as colour-coded tables.

The experiment involved 26 participants, randomly divided into 8 teams, who were given a fictional design problem related to the task of redesigning a consumer product under the light of making it more profitable from a lifecycle perspective. The input for the exercise was a value assessment report, articulated on 5 main value dimensions (Operational Performance, Servicing, Logistics, Manufacturability and Intangibles) and related value drivers, for each of the 7 main product building blocks. Half of the teams were provided with a report featuring the colour-coded tables, while the other four with the colour-coded models. After making the participants aware of the problem context and objectives, they were given 30 minutes to brainstorm solutions, 15 minutes to select and prototype the selected concepts and 15 minutes to fill a questionnaire on the design session's results.

The authors made use of 26 micro strategies grouped in 4 main categories, similar to what proposed by Gero and McNeill [39], which is acknowledged as one of the most detailed and successful coding schemes for the analysis of protocols [40]. The protocol analysis was complemented by a Likert-scale questionnaire featuring 8 statements about the effectiveness and the usability of the approach.

### 8.1 Results from the laboratory experiment

As shown in Figure 2, during the problem analysis phase, the teams using colour-coded CAD models dedicated 222% more time in analysing and discussing the value report (53.80%) compared with the teams using tabular visualisation (28.25%). For the teams with colour-coded models this micro strategy alone counts for 10% of the total time allocated for the session.

The teams using colour-coded models have also dedicated 20.98% more time in proposing a solution, compared to the groups using tabular reports. Similarly, they have spent more time (22.85%) to clarify a proposed design solution.

The groups with colour-coded models also show a tendency toward proposing solutions that are not
retracted during the session. This has caused an average reduction of the total time spent on this activity of the 1.02%, 31.41% less time compared to the tabular visualisation format.

The questionnaires show that colour-coded 3D CAD models outperform tables in terms of usefulness for developing a new solution (+20%) and awareness of the value assessment report data (+13%).

9 CONCLUSIONS
Emerging from an empirical study in the European aerospace industry, the paper has proposed an approach that uses colour-coded 3D CAD models to visualise and communicate the value contribution of alternative sub-system technologies during preliminary design, as a means to guide value trade-offs at the decision gate.

In the authors' advice the concept of "value" can complement SE practices in the preliminary development stage of aero-engine components, providing means to communicate the overall intent of a design across individuals and teams, thus supporting early design concept selection. Value can encourage a more extensive interdisciplinary requirement analysis and validation dialogue in early phases, to obtain a base of shared knowledge and system models.

The study have highlighted a set of preferences towards value visualisation, which have been used as a basis for the development of a methodological/technological approach, further implemented in a commercial CAD/PLM environment. The results of the certification activities performed so far indicates that the approach proposed, based on colour-coded 3D models, may increase the decision makers' awareness of value-related information during preliminary design, stimulating the analysis of the value assessment report and the discussion on value-related matters – to complement traditional requirements-based information. Such results will further be validated by means of new experiments and by coding the video and audio recording from the sessions.

Eventually, the high level benefits that implementation of the approach aim to contribute to the PSS design process are: 1) cost could be reduced by preventing late changes due to non value adding solution strategies that "consume" time and resources; 2) lead-time could be reduced by identifying and instantiating the optimal direction for technology development in an early phase of the project, 3) rework caused by the late discovery of the impact of an innovative concept at system level could be reduced.

10 ACKNOWLEDGMENTS
The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 234344 (www.crescendo-fp7.eu).

The authors would also thank Gilles Dubourg and Henk Broeze (SIEMENS PLM Software) for their support.

11 REFERENCE


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