Value Assessment Capabilities in Early PSS Development
A Study in the Aerospace Industry

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Preface

The work leading to the writing of this thesis was carried out within the Functional Product Development (FPD) research area in the division of Innovation and Design at Luleå University of Technology. The research received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement No. 234344; thus, acknowledgment goes to the European Commission and CRESCENDO.

My close collaboration with industrial partners has provided fundamental support for my research; thus, I am grateful to all the collaborative companies—particularly Volvo Aero Corporation, whose close support has significantly improved the quality of my work.

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Last but not least, I offer my greatest gratitude to my family for always supporting me during this process and to my beloved Clizia for the invaluable quality of making my life better even from three thousand kilometers away. Without you, none of this would be possible.
Providing added value to standalone products by adding services is at the core of product service systems (PSS) offered in manufacturing industries. Providing PSS requires a change not only in the way products are sold, but also in the way they are designed and developed. Engineers need to assess the value of a forthcoming PSS solution as soon as possible in the design process, addressing service-related issues that often fall outside their technical horizon and are challenging to seamlessly translate into the product technical requirements. The aim of the thesis is to investigate the early stages of aerospace product development, proposing methods and tools in order to improve the decision-making process, by enhancing the awareness of engineers and designers about the value contribution of different design alternatives.

This academic work was performed through action research in close collaboration with major European aerospace manufacturers, research centers, and academic institutions conducting research in product development. The thesis first depicts the current practices and limitations of value assessment in early design stages, describing the increasing complexity of the aerospace development projects. Improvements for current practices are proposed in terms of developing value assessment capabilities coupled with requirements analysis and enhancing communication of the expected value contribution of a forthcoming solution.

Second, this thesis proposes a conceptual approach aiming to enhance the communication between engineers and designers of the value-related aspects of a solution in early design stages. This approach allows for the visualization of the results of a value assessment activity using color-coded features on the product’s computer aided design (CAD) model. The characteristic of the approach is to allow for the simultaneous visualization of value scores and knowledge maturity in a unique representation. The approach is meant to increase the awareness about the multifaceted aspects of the value assessment of different designs, promoting tradeoff and impact analysis.

In conclusion the thesis summarizes the findings of the empirical analysis, showing the need to complement requirement information with the assessment of value and knowledge maturity, and proposing color coded CAD models as technological enabler for the communication of the outcomes of the value assessment. Finally guidelines for future research are provided.

**Keywords**

Thesis

This thesis comprises an introductory part and the following appended papers:

Paper A:


Paper B:


Best Paper Award “The Service Lion” at the 3rd CIRP conference on Industrial Product Service Systems.

Paper C:


Related Publication

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1 Introduction

The introduction comprises a discussion of the background of my work, followed by the statement of the aim and research questions. Research motivation and delimitations are further described focusing on the context of applicability of the work.

Since the beginning of the industrial era, competition has affected the way in which manufacturing firms have developed, produced, and provided products and services to customers (Porter, 1998; Marsili, 2001; Isaksson, 2009). Manufacturing companies have traditionally focused their design and development activities on realizing the technical and engineered aspects of physical artifacts (e.g., Pahl and Beitz, 1996). The enormous changes affecting society and the economy during the twentieth century forced industries to continuously modify and innovate the approach toward the development of new products (Brown, 1995). In the last decades, the increasing competition within the global market has driven manufacturing companies worldwide to reconsider the traditional concept of goods production. Companies have begun to realize that gaining a competitive advantage and expanding market shares are not achievable purely through continuous technical improvements; rather, they require a deeper understanding of customers’ expectations, needs, and perceived value scales (Woodruff, 1997).

Companies have been forced to radically rethink aftermarket activities and consider themselves not only as product sellers, but also as service providers (Oliva, 2003). Initiatives such as Product Service Systems (PSS) (Manzini 2001; Tukker 2004; Baines 2007), Functional Products (Ericson, 2006), and Integrated Product Service Engineering (Lindahl 2006), reflect the shift toward this new offers.

This transition involves a radical change; not only in the way the products are offered, but also in the way they are designed and developed. The focus of the design activity shifts from the definition of new products to the re-organization of existing elements based on new needs and values (Morelli, 2003), thus the designer’s role consists of synthesizing customer’s, provider’s and society perspective (Östlin, 2008).

This context requires designing products that meet engineering requirements while simultaneously providing greater value for the customers, considering the new ownership structure of a PSS. Hence, developing a PSS is not merely a matter of choosing the best technical solution but is rather about finding the best combination of products and services to maximize stakeholders’ and customers’
value. However the selection of the favorite design alternative is not straightforward, as guidance is needed to translate customers’ and business stakeholders’ desires into terms that are immediately meaningful to PSS engineers.

1.1 Designing PSS in the Aerospace Industry

In the last decade, aerospace companies have become increasingly interested in integrating more service aspects in their offers. Rolls Royce Aerospace provides a clear example of the shift toward providing PSS through its TotalCare offer. The company offers a total care package embedding operational support, repair, overhaul, and information management (Rolls Royce, n.d.), and customers buy the capability that the engines deliver “power by the hour.” Thereby, Rolls Royce Aerospace retains the responsibility for risk and maintenance and generates revenues by making the engine available for use (Neely, 2007).

The design of services and hardware in a coordinated development process affects work organization as well as the tools and methods needed (Alonso-Rasgado, 2004; Isaksson, 2009). The effort of orienting a collaborative design process toward the maximization of the value provided is well synthesized by the Value Driven Design (VDD) system engineering strategy (Collopy, 2009). VDD promotes the use of value as the key concept for driving the design activity not only to evaluate designs or help determine requirements, but also to drive major and minor design choices throughout the whole process. VDD uses a mathematical model built using a set of predefined relevant value parameters to run multidisciplinary design optimization.

Running a VDD optimization requires the presence of a set of values that are quantitatively measurable. However, in early design stages, detailed information about the future product and service is seldom available. In addition, key factors to the product’s success that directly impact customers’ and stakeholders’ perceived value, but that are not directly referable to economics measures, must be considered. For instance, in the aerospace industry, comfort and on-board service quality are relevant values that could drive the end user’s choice, but these are not easily translated in economic values for use in VDD optimization.

1.2 Research Aim and Research Questions

The aim of the thesis is to investigate the early stages of aerospace product development, proposing methods and tools in order to improve the decision-making process, by enhancing the awareness of engineers and designers about the value contribution of different design alternatives. The research questions can be stated as follows:

*How can the assessment of value contribution of different design alternatives be supported in early development stages?*

*How can the communication of value-related information be supported in early development stages?*
These questions are addressed by adopting the perspective of aerospace product development processes in order to support the development of innovative solutions, taking into consideration the integration of service aspects into the traditional product offer.

1.3 Research Motivation

In a new development paradigm, the Advisory Council for Aeronautics Research in Europe (ACARE) identified the major challenges for the design of new aircrafts. The ACARE Strategic Research Agenda 2 (ACARE, 2004) set five high-level target concepts, defining the guidelines for the future aerospace development processes. According to the targets, the new air transport system should be:

- Highly customer oriented,
- Highly time efficient,
- Highly cost-efficient,
- Ultra green, and
- Ultra secure.

In order to achieve the ACARE targets, the aerospace industry needs to approach the problem from different angles. The evolution of the business models, together with a strong demand to reduce lead times and develop more cost-effective solutions, has forced companies to face greater challenges than ever before. The examples of the last aircrafts designed by Airbus and Boeing—namely, the Airbus A380 and the Boeing 787 Dreamliner—introduced several technologies never previously used and the collaboration of hundreds of suppliers worldwide, from design to manufacturing and assembly (Boeing, n.d.; Pardessus, 2004). Such evolution is also driven by the fact that aspects such as comfort, timeliness, entertainment, and environmental consciousness are emerging driving forces in new aircraft development programs (Boeing, 2006; Airbus, n.d.).

On a more technical level, this evolution has translated into a number of altered functions on aircraft parts. Engines, for instance, need to improve the efficiency in energy use (Provost, 2002), which turns into new requirements that affect not only the aircraft provider, but also all companies involved in the supply chain, thereby affecting the way in which engines and engine components are designed.

Supply chain partners need to deliver new technologies and new designs by understanding the value and impact that a part or component will have on the final product (i.e., the aircraft). However, research has shown that remarkably few firms have the knowledge and capability to actually assess value and, consequently, gain an equitable economic return for the innovative product or technology delivered to the customer (Anderson, 1998). This process is relatively difficult as it implies the acquisition of an enormous knowledge base about the
system behavior. Despite the effort being spent by aerospace company in facing this problem, important design decisions may be based on a limited, heterogeneous, and poorly mature set of information.

This situation calls for a methodological and technological approach to enable the assessment and the communication, in an objective and transparent way, of the potential value contribution of a new solution in order to identify the preferable technology or component to be developed among the different tiers of the supply chain as quickly as possible in the design process.

1.4 Delimitations

The research was performed in close collaboration with a major component manufacturer in the European aerospace industry, and the results have been discussed primarily with aircraft and engine manufacturers. The focus on aerospace companies is therefore predominant in the thesis as well as in the appended papers. This limits the scope of generalizability to aerospace manufacturing and generalizing the results to other contexts will therefore require further investigation.

1.5 Thesis Outline

This thesis consists of six chapters. Chapter 1 introduces the work describing research motivation, aim, and research questions and identifies the delimitation of the work. Chapter 2 describes the methodology and the methods used in the research work, including how the data were collected and analyzed and discussing the research quality. Chapter 3 describes the theoretical areas relevant for the thesis (i.e., PSS, value, VDD, and decision making). Chapter 4 provides a brief description of the appended papers and their contribution to the thesis. Chapter 5 describes the findings of the thesis, identifying needs and challenges in aerospace product development, proposing an approach to improve the current process. A Lightweight Value Visualization tool is presented to visualize the value contribution of a forthcoming solution in a CAD environment. Finally, Chapter 6 summarizes the conclusions and introduces future work.
2 Methodology

This chapter presents the approach through which the work was performed. It describes action research as the methodology adopted and DRM as the guiding framework in the research process. Research environment, data collection and analysis are described, and at the end a reflection about the research quality is presented.

2.1 Research Methodology

The research can be methodologically likened to action research. According to Avison (1999, p94), action research is a qualitative research methodology “particular in the way it associates research and practice, so research informs practice and practice informs research synergistically”. The concept of action research was first coined in the 1940s by Professor Kurt Lewin at the Massachusetts Institute of Technology, defining it as “a comparative research on the conditions and effects of various forms of social action and research leading to social action” thanks to the use of “a spiral of steps, each of which is composed of a circle of planning, action, and fact-finding about the result of the action” (Lewin, 1946 p35, p38). In the beginning of the 1970s, Rapoport (1970, p499) contributed to the definition of action research specifying its ambition “to contribute both to the practical concerns of people in an immediate problematic situation and to the goals of social science by joint collaboration within a mutually acceptable ethical framework.”

Action research involves the direct participation of researchers and practitioners in the research process and can be used to increase the understanding of how a change in one’s action or practice can positively impact the “community of practice” (Mcniff, 2002; Wenger, 1998). Action research is also beneficial for understanding ill-structured problems of complex organizations and is characterized by learning circles in which the researcher wants to test a theory with practitioners in real situations, gain feedback from this experience, modify the theory as a result of this feedback, and try it again (Avison, 1999).

A potential problem when adopting action research to study the design process emerges when researchers and practitioners are unlikely to share information. This issue could arise because of personal conflicts between people or because of changes in companies’ policies (e.g., low interest in the research projects, IP issues, unwillingness to share findings). Such an issue could paralyze the research process, causing the research network to underperform and making it cumbersome to physically test the theory or methods, thereby breaking the learning cycle.
2.2 Research Framework

In order to provide a framework for the research process, the Design Research Methodology (DRM) proposed by Blessing and Chakrabarti (2009) was used to plan the research work. Using the DRM was expected to help addressing the issue of reducing the research to a problem-solving activity (Blessing, 2009). This is given by the strong focus on addressing issues and solving problem in an industrial setting, causing the risk of lacking of overview in the existing literature.

DRM consists of four stages—namely, Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II.

The Research Clarification stage and the first Descriptive Study have been run concurrently since the beginning of the research activity.

During these two parallel stages, an investigation—mainly through literature review, documents, company site visits, and interviews—was performed. Based on the preliminary findings, an initial description of the situation to be studied was developed, clarifying existing understanding and expectations as well as defining the main questions.

The research has also moved into a more prescriptive stage, where—using the knowledge acquired—the vision toward the improvement of some factors was addressed and innovation and modification of the process were proposed. During this stage, the color-coding approach (see Chapter 5) was conceived.

The research described in this thesis encompasses the first three stages of the DRM and has not yet moved into the Descriptive Study II phase. Here the impact and the performances of the proposed solution will be evaluated to determine if the proposed approach can be used for the task for which it is intended, and whether the expected impact has been realized. Ultimately, the necessary improvement to the concept/approach/tool will be proposed.

When looking at DRM as guide for this work it has to be considered that a lot of concurrent work and overlapping activities have been run in order to define and refine the proposed solution, thus it is not possible to consider the phases as run sequentially. Figure 1 summarizes to which stages of DRM the appended papers relate.

![Figure 1: Correlation between appended papers and DRM model.](image-url)
2.3 Research Environment

The research has been performed in the frame of a European Commission’s research project within the EU FP7 programme. The project, named Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation (CRESCEndo), has the goal to deliver the modeling and simulation backbone of the aeronautical extended enterprise: the Behavioral Digital Aircraft, identified as the missing capability which will enable the use of simulation throughout the development life cycle at aircraft level and in the entire supply chain. The project has involved 59 academic and industrial partners, representing a cross section of European aeronautics. This thesis has been performed inside a specific work package, and has focused on changing the way product development is initiated by developing innovative mechanisms:

- To capture, model and understand customers, and stakeholders, needs and expectations.
- To incorporate the value dimension into preliminary design in the virtual extended enterprise.
- To identify criteria and indicators that can be used in preliminary design studies that affect customer perceived value.

More in detail the work package partners cover a large part of the aeronautical supply chain representing an aircraft manufacturer, with its parent company, an aircraft engine manufacturer and a component manufacturer, also defined as subsystem manufacturer. In addition the project has given access to a number of companies specialized in IT solutions for enterprise collaboration and CAD/PLM software.

2.4 Data Collection

Different data collection methods were applied during the various steps of the research. These activities were not conducted sequentially, but the different methodologies ran in parallel, contributing to the continuous improvement of a solid set of relevant and appropriate prerequisites essential to the study (Preece, 2004).

Informal communication and face-to-face discussions were a relevant part of the data collection. High-quality informal communication in a research team is important to develop common interest on the topic (Kraut, 1988). Indeed, researchers perceive frequent face-to-face discussion as the most interactive and intellectually exciting aspect of the research process (Kraut, 1988). The discussions took place during company site visits, conferences, formal project meetings, and informal occasions. Notes were taken either during or soon after the discussions. Sketches on papers or whiteboard were often the output of such discussions, and data were collected by either photographing or collecting the materials.

Semi-structured interviews (Yin, 2009) were also used as data source in the research. These interviews were scheduled in advance in a designated time and
date; they were organized around a set of predetermined open-ended question, with additional questions emerging from the dialogue (DiCicco-Bloom, 2006). This methodology allowed the detections of behaviors in the state-of-the-practice, which were impossible to capture through informal conversations, narrowing the focus of the discussion into more specific issues. Semi-structured interviews took on average from 30 minutes to one hour, and the information acquired was transcribed by the author and validated by the respondents. In most of the cases the interviews were audio-recorded and transcribed later. When audio recording was not possible notes were taken during the interview, and a summary of the content was written soon after the activity.

Workshops were also used as a tool to help groups of people, either in companies or in academies, to work more effectively together on common tasks (Brinkeroff, 1994). Two workshops took place during the research: one at a partner company and one in an academic environment. The workshop held in the company setting took half a day and involved company experts from marketing and product development. The workshop highlighted product and technology innovation trends in aerospace from a component manufacturer perspective, providing contextual knowledge and information necessary for the research problem clarification. Meanwhile, the second workshop was organized as a four-day activity conducted in an academic environment, involving researchers specialized in PSS development and innovation. It provided an explorative vision on future issues and needs for value communication in PSS development, providing insights and guidelines on how to approach the research project from an academic research perspective and how to build the work on the current knowledge. The materials (e.g., post-its, papers, sketches) generated during the workshops were collected and categorized. Pictures of whiteboard, prototypes, and sketches were taken, and the information was further analyzed and summarized in text files and figures.

A number of short- and long-term company site visits were performed during the research. A five-week visit at a project partner was performed during the first months of the research. This visit proved to be fruitful in order to create the links in the research network and to begin the description of the state of practice as well as the identification of the issues and challenges necessary to define the research question. The author had access to company documents and descriptions of formalized processes, and to company experts and specialists, to gather data about how concept development activities are performed in the industry. A number of multi-day meetings were held by each partner company, including the participation of all project partners, with the intent of sharing the findings of the individual research and coordinating the future action plan.

Finally, weekly virtual meetings, held by telephone and video sharing, were run to share information and data as well as enhance the project team coordination.
2.5 Literature Review

The research included a literature review carried out in different phases. Initially literature was used to define the research problem by examining previous works and developing a deep understanding of the research area related to engineering design. The existing literature concerning different design strategies was studied in order to identify strengths and gaps related to VDD as well as build a coherent understanding of the concept of value. The second phase of the research included a literature study in order to investigate the previous publications related to visualization in product design.

The literature research strategy was first developed by identifying relevant keywords; then it was run on a wide set of databases (i.e., Scopus, Web of Science, Scirus, and Google Scholar). The most used keywords for the research were “product service system design,” “value assessment,” “value visualization,” “value communication,” “value driven design,” “early design stages,” and “decision making.” The articles selected for further readings were those perceived to be close to the research area after reading the title, abstract, and conclusions; the number of citations and date of publication were also parameters considered to evaluate the relevance of the papers during the selection process. Colleagues and supervisors also provided guidelines in the literature selection process. Participation in international doctoral courses, workshops, and conferences involving both industrial and academic experts served as a guide in the selection and review process and in avoiding bias in literature selection and analysis. Several distinguished journals and conference proceedings were used in the literature studies.

The main functionalities and features in today’s commercialized CAD software were analyzed as well, accessing the information published on the websites of the main CAD/PLM providers.

2.6 Data Analysis

An analysis of the collected material was performed. The analytical lens focused on the concept of value, including how this can be measured and how people deal with it in product development. The contents of the weekly virtual meetings were transcribed and summarized in plain text soon after each meeting. The same was done for the notes of the meetings that took place during company site visits. These transcriptions were made available to the whole research group by publishing them on the project web portal, to which access was limited only to the project members. The transcripts were then read through and reflected upon both from a holistic and detailed perspective. The transcription also helped analyze how the problem definition evolved during the project. The analysis of the transcriptions focused on the identification of recurrent issues and

1 www.scopus.com
2 apps.isiknowledge.com
3 www.scirus.com
4 scholar.google.com
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challenges; thus, different themes emerged as relevant topics of research, leading to the definition of the final research question. Furthermore, data were used to design and validate the value visualization approach. Frequent discussions with co-authors, supervisors, and project leaders were held to summarize data collected and reflect upon their meaning.

2.7 Research Quality

Being able to assess quality is a critical aspect to be considered when evaluating research in order to understand the real value of the findings. Qualitative research has been often criticized for lacking of scientific rigor encountering the risk of being an assembly of anecdotes and personal impressions, strongly subject to researcher bias (Mays, 1995). The basic strategy to ensure rigour in this thesis is a systematic and self conscious research design, data collection, interpretation, and communication (Mays, 1995).

In action research, the research context and the phenomena are not homogeneous through time and it is not possible to recreate an ad-hoc setting in order to replicate the research as it was, thus replicability of results is not possible (Checkland, 1998). The problem in action research, knowing that the strong criterion of repeatability is not reachable, is to do better than simply settle for plausibility (Checkland, 1998). Action research must at least achieve a situation in which the research process is “recoverable by anyone interested in subjecting the research to critical scrutiny”, also by declaring in advance the methodology (encompassing a particular framework of ideas) (Checkland, 1998 p13). If this situation is met, the generalization and transferability of results will be easier justifiable (Checkland, 1998).

The recoverability of the study was achieved by adopting methods largely verified and consolidated in literature and practice, in order to minimize the errors in both the data collection and the data analysis. All information managed during the research was collected and stored while keeping track of the rational hidden behind the decisions.

Additionally, as stated by Greenwood and Levin (Greenwood 2000, p96), credibility, reliability and validity are “measured by the willingness of local stakeholders to act on the results of the action research, thereby risking their welfare on the “validity” of their ideas and the degree to which the outcomes meet their expectation”, and core validity is based on the “workability” of the social change and on the test of whether or not the actual solution solved the original problem.
3 Theoretical Framework

This chapter introduces the theoretical areas that are relevant for the research, giving the reader an awareness of the basis of this work. The chapter focuses on four areas: Product Service Systems, Value, Value Driven Design and a deeper theoretical description about Decision Making and how to support it.

3.1 Product Service Systems

A PSS can be seen as a business model whereby manufacturing companies provide a mix of both products and services instead of only focusing on products (Mont, 2004). Several authors have contributed to defining PSS. For example, Goedkoop (1999, p18) defined PSS as "a marketable set of products and services capable of jointly fulfilling a user's need." Similarly, Mont (2001, p239) described PSS as "a system of products, services, supporting networks and infrastructure that is designed to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models."

Additional definitions do not explicitly state the connection between PSS and reduced environmental impact. Manzini and Vezzoli (2003, p851) defined PSS as "...an innovation strategy, shifting the business focus from designing (and selling) physical products only, to designing (and selling) a system of products and services which are jointly capable of fulfilling specific client demands." Tukker (2004, p246) stated that PSS “...can be defined as consisting of tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs.” The peculiarity of early design stages of PSS shifted the focus from the creation of a new product to the “re-organization of existing elements on the basis of new needs and values” (Morelli 2003, p75).

Cook (2006) categorized PSS into three groups differentiated by product ownership and type of service provided. These categories are:

- **Product-oriented PSS.** This category includes the PSS offers in which the ownership is transferred to the customer and a service arrangement is provided to “ensure the utility” of the product. Notable examples are warranties and maintenance contracts.
- **Use-oriented PSS.** In this category, the customer purchases the use of the product over a given period of time or units of service. Typical examples are leasing contracts or product sharing.
- **Result-oriented PSS.** In this case, the company sells a result instead of a product. The customer buys an expected outcome and not a “use of a product over a given period of time” (Cook, 2006).
Williams (2006) provided several examples of result-oriented PSS, concerning both “pay per service unit” and “functional result” achievements. Tukker and Tischner (2006) summarized the PSS categories by highlighting their differences in terms of value provided to the customers (see Figure 2). They underscored how PSS cover the gap between pure products, whose value is mainly in product content (i.e., tangible), and pure services, whose value stems primarily from service content (i.e., intangible).

A more recent definition of PSS was provided by Baines (2007), who described them as a special case of "servitization"—namely, a market-led approach that extends the traditional functionality of a product by incorporating additional services. PSS emphasizes the “sale of use” rather than the “sale of product”: “the customers no longer pay for the ownership of a product, but pays for using an asset or achieving a result, thus avoiding additional costs associated with ownership” (Baines 2009, p294).

3.2 Value

Existing literature reveals a wide diversity of opinions and many speculative assertions on the real meaning of value. Despite the centrality of the value concept, relatively little knowledge exists about what value is, what its characteristics are, and how stakeholders determine it (Day, 2000).

The concept of value has been examined by various authors with other notions. Monroe (1990) defined it as the perceived benefit received relative to price. Butz (1996) defined value as an emotional bond established between a customer and a producer, whereas Woodruff (1996) referred to value as the perceived trade-off between the positive and negative consequences of product use.

Miles (1972) first introduced the value analysis concept, intended as a
problem-solving system and an organized creative approach for the efficient identification of unnecessary costs (i.e., costs that do not contribute to quality, use, life, appearance, or customer features). From such a perspective, a product or service is generally considered to have good value if it has appropriate performance and a low cost. By reverse definition, a product is considered to have bad value if it lacks appropriate performance and has a high cost. In this sense, the value of a product can simply be expressed as the ratio of its performance to its cost. Zeithaml (1988) provided a different definition, identifying value as the ratio between what the customer perceives to receive and what he/she gives. This definition points out the subjective and individual nature of perceived value. Building on Zeithaml’s definition, Ravald and Grönroos (1996) underscored how customer-perceived value cannot be derived just from the core product and the related supporting services; rather, it has to include the effects of maintaining a relationship with the customer. Thus, trust and good relationships are additional value drivers in a business offer.

Anderson et al. (1993, p3) defined value in business markets as the “perceived worth in monetary units of the set of economic, technical, service, and social benefits received by a customer firm in exchange for the price paid for a product offering, taking into consideration the available alternative suppliers offerings and prices.” Kelly and Male (1993, p15) similarly described value as “a measure expressed in currency, effort, exchange, or on a comparative scale which reflects the desire to obtain or retain an item, service or ideal.”

According to the surplus-value theory (Collopy, 2002), independently from market concurrency, a successful product has to maximize the value provided to the final customer; meanwhile, the market divides the value among the companies of the supply chain. Nagle and Holden (1994) highlighted not only how market value determines the product’s economic value, but also how buyers perceive that value and how much importance they place on getting the most for their money. Buyers may inaccurately perceive value because they are unaware of the product’s or service’s value or they are not persuaded that the product or service delivers the value promised by the provider.

Porter (1985) sought to categorize value according to nine generic company activities, dividing company value into two main dimensions: primary activity and services. A different categorization not linked to company activities is provided by Neap and Celik (1999), who highlighted three types of value:

- Objective value (the value that buyers actually receive);
- Subjective value (the value buyers perceive that they receive); and
- Experiential value (the value buyers perceive as weighted psychologically by the salience of different dimensions both tangible and intangible—i.e., value related to the subjective desire to obtain or retain a product).

Shapiro and Jackson (1978) and Forbis and Mehta (1981) conceptualized objective value in relative terms as the maximum amount a customer should be willing to pay, assuming full information about the product and competitive
In addition, value is often seen as intangible (Steiner, 2009), created by people (Bowman, 2000), and perceived by the customer as an individual rather than objectively defined by a provider (Kauppinen, 2009). Goods and services can be arrayed along a continuum of relative tangibility, with goods being more tangible and services more intangible (Vargo, 2004). Intangibles are often associated with knowledge, emotions, and experiences—dimensions that cannot be experienced by the customer before using the product. Steiner and Harmor (2009) proposed an extended model of customer value that includes intangible criteria (e.g., epistemic emotional or image value) to be used for assessing the overall value of a system in the beginning of a product development project. Along the same line, Kowalkovski and Kindström (2009) identified three broad categories of value perceived by customers when dealing with PSS offerings:

- Product-based values, such as performances, quality, and unit price;
- Service-based values, such as operation costs, customization benefits, and service consistency; and
- Relationship-based values, based on the idea that a supplier and a customer maintain a relationship over time, thereby including value such as proactivity, trust, long-term commitment, and shared norm and mindset.

### 3.3 Value Driven Design

VDD is a system engineering strategy promoting the use of multidisciplinary optimization in design. According to Collopy (2009), VDD “is not a new method, process, or tool for design. Rather, it is a framework against which methods, processes, and tools can be assessed.” VDD impacts the way in which designers deal with extensive attributes (i.e., in those attributes of a complex system whose value is a function of the values at the component level) (Collopy, 2007). Examples of extensive attributes are weight, performance attributes, safety, and all attributes related to costs (Collopy, 2009). In VDD, no requirements are applied to extensive attributes; these are substituted by objective functions assigned to each design team and translated into the team’s full set of attributes into a design score. The design team’s task is then to create a design that yields the highest score on extensive attributes while fulfilling the requirements of the non-extensive attributes (Collopy, 2009). In a VDD approach, objective functions need to be cascaded down to each component and the status of component attributes need to be monitored together with the status of system attributes to drive appropriate actions to maintain a balanced system (Collopy, 2009). Figure 3 shows the VDD process as described by Collopy (2009).
The evaluation phase (upper left arrow in Figure 3) differentiates VDD from traditional system engineering. Instead of focusing merely on configuring and balancing the system, the design is assessed based on an objective function, also called the Value Model, which associates a scalar score to each set of attributes. If the current configuration has a higher score compared to previous configurations, the design team can accept the product configuration or try to produce a different design with additional improvements going through the loop again. VDD should not be seen as an optimization process, but as a framework enabling the use of optimization during design; thus, designers are free to use their favorite judgment variables during the design cycle (Collopy, 2009).

According to Collopy (2009), VDD provides three major benefits to the design of a complex system:

- VDD enables and encourages design optimization for the whole system during early design phases and for each component during the detailed design.
- VDD prevents design trade conflicts, thereby preventing dead loss trade combinations.
- By eliminating requirements for extensive attributes at the component level, VDD avoids the cost growth and performance erosion caused by requirements.

Some examples of VDD application are provided in the literature; most papers are delivered by members of the Value Driven Design Institute and focus on aerospace design. For instance Brown and Eremenko (2008) described the case study application for fractioned spacecraft development; meanwhile, Collopy
Value Assessment Capabilities in Early PSS Development

(1997; 2006) described the VDD application in the building of a model of an aircraft propulsion system and during a workshop to develop a value model for a global positioning system. Another example of VDD application was provided by Castagne, Curran and Collopy (2009), who described the implementation of value-driven optimization for the design of aircraft fuselage panels.

3.4 Decision Making

Ulrich and Eppinger (2008) stated that all design teams follow structured rules or guidelines for selecting different concepts and solutions. However, in practical situations, rational decision making is rare (Simon, 1979). Large-scale development processes commonly involve phases that incorporate planned decision points. The Stage-Gate® process (Cooper, 2008) is a typical approach toward decision making in large and complex product development projects. Stage-Gate® is composed of a “stage” in which activities take place and a “gate” whereby information is assessed and decisions are made. Essentially, the gates are collaborative decision-making points where individuals, teams, and organizations join forces to carry out their work as effectively as possible in an attempt to guarantee a confident “go” decision at every gate.

According to the design process paradox (Ullman, 1992), the more the team learns, the less freedom it has to use what it knows (Figure 5). Designers are in the unfortunate situation of having limited knowledge about the forthcoming solution in the early stages, when they have good opportunities to influence the design; meanwhile, when they have established a more developed knowledge base in the later stages, major decisions have already been made and capital has already been committed, making it more costly and time-consuming to make changes.

Multi Attribute Decision Making (MADM) is a common decision-making approach used when decision makers need to select, or rank, alternatives associated with non-commensurate and conflicting attributes (Fan, 2002). In its most basic form, MADM assumes that a decision maker has to choose amongst a
set of alternatives whose objective function, values, or attributes are known with certainty (Dyer, 1992). Designers need to rank different alternatives and then choose the option that maximizes the overall sum of attributes ranked. However, in reality, it is impossible to anticipate all the consequences of a decision as all the alternatives are seldom known (Simon, 1979).

During the early design stages of innovative projects, designers have limited knowledge about the future evolution of the design since the condition changes over time. Thus far, gut feelings and intuition play an important role in the decision-making process (Ericson, 2007; Hart, 2003). According to Hayashi (2001) and Eisenhardt (1990), emotions, intuition, and experience become key qualities when making decisions not supported by an adequate level of information. Making a decision can often end up in settling for what is good enough rather than waiting for the optimal solution to emerge (Simon, 1979).

3.4.1 Visualization Support for Decision Making

Benefits and risks of information and knowledge visualization in decision-making activities have been largely discussed in literature. They mainly concern the study of the dynamics of decision-making meetings, what influences people’s decisions, and how this process can be enhanced to reduce uncertainty and subjectivity.

The theory of cue-summation (Severin, 1967) proposes that the use of multiple cues creates advantages by enhancing associative processing and mitigating information overload. However, Severin pointed out that filling different information channels with as much information as possible will most likely evoke irrelevant cues adding extraneous association that will result in more irrelevant cues than relevant ones.

As Bresciani (2008) noted, business meetings have the characteristic of being multimodal—namely, in addition to the verbal communication and sharing of knowledge, most meetings include shared and distributed visual representation.
Moreover, because of the wide scope of decisions to be taken, managers often delegate analysis and decision preparations to experts or collaborators (Eppler, 2007). Thus, such analysis needs to be communicated back to the managers, who have to make a decision in a restricted time frame (Eppler, 2007).

The problem generated by information overload is constantly present (Tegarden, 1999), and 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. Tegarden (1999) identified in visualization technologies the tools enabling decision makers to fly over, or swim through, the data. Information visualization is defined by Card (1999) as the use of computer-supported, interactive, visual representations of data to amplify cognition and generate various benefits, such as:

- Increasing the memory and processing resources available to the user;
- Reducing the search for information;
- Using visual representations to enhance the detection of patterns;
- Enabling perceptual inference operations;
- Using perceptual attention mechanisms for monitoring; and
- Encoding information in a manipulatable medium

Eppler (2004) referred to knowledge visualization using a similar definition: “The use of computer-supported, interactive visual representations of insights, assessments or expert opinions to amplify communication.” Through the use of experiments, he confirmed that interactive visualization tools offer great potential for the improvement of (synchronous) knowledge communication. He stated that the potential to combine various formats of visualization in a complementary way seems to be a promising strategy toward knowledge visualization (Eppler, 2007).

A number of experiments demonstrate the effectiveness of knowledge and information visualization in the decision process. Dull and Tegarden (1999) compared three different representations of complex multidimensional accounting information, concluding that the multidimensional visual representation of complex multidimensional data results in greater decision-making accuracy as it facilitates the direct examination of the complex relationships in the data. They noted the necessity of having a representation of the interactions among the variables to enhance the decision-making accuracy when the variables increase in complexity. Bresciani and Eppler (2009) analyzed the impact of visualization on knowledge sharing in 26 groups of managers. The analysis indicated that groups supported by extensive visualization achieve higher productivity, higher quality of outcomes, and greater knowledge gains. The experiment demonstrated that interactive visualization facilitates knowledge sharing, thereby increasing individual learning and team performances.

Eppler (2006) reflected upon the effective use of information and knowledge visualization during decision-making meetings. Replacing elaborated, text-based argumentations with implicit assumptions may lead to ambiguous
communication and misunderstandings, if the visualization is not well explained, presented, and documented (Eppler, 2006). Visualization problems can be linked to technical issues, but can also be closely tied to the cognitive styles, personal characteristics, and prior knowledge of visualization audiences (Bai, 2011). According to Bai (2011), many problems can arise due to the lack of consideration of purpose and context for which the visualization has been created.

3.4.2 Color-Coded Visualization for Decision Making

The influence of color and graphical information presentation in a managerial decision environment is an argument that has been discussed since the 1970s. Color emerged as one of the key cues for enhancing knowledge and information visualization in decision-making activity for several reasons.

Colors have been found to be the most effective coding technique for aiding visual searches (Christ, 1975). Properly used, colors have been found to improve the usefulness of an information display system (Murch, 1984). Chute (1979) stated that color’s ability to delineate figure-based relationships, show interrelatedness, and make discrimination underscores color’s effectiveness in learning. A subsequent experiment conducted by Benbasat (1986) indicated that color has several beneficial effects for decision making. Subjects with color-coded reports managed to obtain a significantly higher average profit over the first 10 trials and completed the task using fewer trials. Indeed, the processing of color precedes the processing of other attributes (Karayanidis, 1997). Further studies have highlighted the importance of colors as supplementary information cues in interface designs to encourage associative processing (McNub, 2009).

3.4.3 Knowledge Maturity Support for Decision Making

Every design decision includes a degree of uncertainty that needs to be handled—perhaps not by directly focusing on reducing the uncertainty, but rather by assisting the decision makers to achieve a better understanding of what those uncertainties, ambiguities, and assumptions actually involve (Stacey, 2003). This uncertainty is even more evident when dealing with value—a concept more difficult to grasp than technical product information.

The concept of maturity (Grebici, 2007) builds on the assertion that everything cannot be known: Some variables are exogenous and uncontrollable whereas others can be controlled. Maturity is intended to be a compromise between the target uncertainty and the expected uncertainty (Grebici, 2007), denoting maturity as the distance between the levels of completeness relative to what should be the level of completeness. It measures the state of the development of a piece of information with respect to achieving a purpose, which implies that a piece of information may be mature for one purpose and immature for another.

According to Johansson (2009), the concept of knowledge maturity can also “assist the identification and assessment of assumptions that are ingrained in the process.” In early design stages, information about the forthcoming solution is often missing whereas reliable knowledge is not available; thus, many decisions are based on knowledge from gut feelings of experienced design team members.
(Flanagan, 2007). However, the risk is that these assumptions are mistaken for proven knowledge and facts (Johansson, 2009).

Johansson (2009) proposed a scale to rate the knowledge maturity level (KML) based on three dimensions—namely, input, method (tool), and expertise (experience)—on a scale from 1 to 5. Johansson (2009) defined 5 as excellent knowledge maturity, meaning that content and rationale have been tested and proven and reflect a known confidence that the procedure to produce the content and rationale reflects an approach where tested methods are used, workers continually reflect and improve, and lessons learned are recorded. Level 4 is defined as good, and level 3 is acceptable (i.e., the content and rationale are more standardized, the procedure is stable and has elements of standardization and repeatability). Level 2 is ranked as dubious, and Level 1 is inferior (i.e., there is a poor understanding of knowledge base, the procedure is dependent on individuals, and formalized methods are non-existent). Figure 6 shows the Knowledge Maturity Scale for input, method, and experience proposed by Johansson (2009):

<table>
<thead>
<tr>
<th>KM LEVEL</th>
<th>Input</th>
<th>Method</th>
<th>Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Excellent</td>
<td>Tested, standardized and verified methods</td>
<td>Long verified experience and expertise</td>
</tr>
<tr>
<td></td>
<td>Input is detailed and verified</td>
<td>that are under continuous review and</td>
<td>within area of concern</td>
</tr>
<tr>
<td></td>
<td></td>
<td>development</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
<td>Standardized and tested methods have used</td>
<td>Proven experience and competence</td>
</tr>
<tr>
<td></td>
<td>Input is available in detailed form, but</td>
<td>methods have been used</td>
<td>within the area of concern</td>
</tr>
<tr>
<td></td>
<td>not verified</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Acceptable</td>
<td>Untried methods have been used (ad-hoc)</td>
<td>Person doing the work is inexperience</td>
</tr>
<tr>
<td></td>
<td>Risk of incorrect input</td>
<td></td>
<td>(first time)</td>
</tr>
<tr>
<td>2</td>
<td>Dubious</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Inferior</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: The Knowledge Maturity scale, from Johansson (2009).

According to Johansson (2009), knowledge maturity supports:

- Putting knowledge at the center of attention and allowing decision makers to focus on highlighting and eventually addressing assumptions, ambiguities, and uncertainties;
- Assessment of the quality of the decision base, thereby looking beyond the face value of documents and focusing on performance-related aspects at gate reviews;
- The ability to focus improvement efforts on areas with low knowledge maturity;
- Confidence for decision makers through raised awareness, thereby enabling them to confidently devise actions and make decisions on a (known) flawed knowledge base; and
- Pragmatic decision making, where an enhanced awareness of the decision base allows for making more confident conditional go decisions.
4 Summary of Appended Papers

This chapter provides a summary of the appended papers, a summary of the main results, their relationship to the thesis, and my role in the division of work between the authors.

4.1 Paper A


Summary

The paper proposes a five-step approach created with the purpose of evaluating sub-system technology concepts from a life cycle perspective. Emerging from the development of an aircraft engine component, the paper shows how the traditional decision making activities focusing on the analysis of component functionalities and performances, can be complemented by a value-oriented assessment to enable more informed life cycle-oriented decisions in early design stages. This is achieved through a process consisting of five main activities: requirement identification and problem decomposition, value drivers definition, concept generation, concept evaluation, and concept selection. The paper contributes to the ongoing discussion about methods and tools to be used in the preliminary design phase to assess the value associated with a design alternative.

Relation to the thesis

Paper A is the result of the work carried out in the first months of the author’s doctoral program in collaboration with a Swedish company operating as an aerospace components manufacturer. During the work, a one-month visit at the company and a four-day visit to an aircraft engine manufacturer located in the UK were undertaken. The study served to build the basic competences for working in the CRESCEndo project, increasing knowledge about the issues and challenges related to the product development processes in aircraft industry. The work also contributed to depicting the description of the state-of-the-practice of the product development processes, enabling the author to become introduced to a cross-company community of practice interested in product development process improvements in the European aerospace context.
Author’s contribution
The author did most of the writing of the paper, formulating the first proposed approach and defining the steps of the process. Ola Isaksson contributed in the improvement loops of the approach and provided useful insights on issues and challenges. Marco Bertoni contributed to structuring the paper and checking the consistency of the concepts, while Tobias Larsson provided the initial idea for the paper and contributed with feedback.

4.2 Paper B

Summary
The paper proposes an approach to support decision making at the gate by increasing decision makers’ awareness about the life cycle value of a set of PSS alternatives. The authors have developed and used a methodology aimed at considering both value—tangible or intangible—and knowledge maturity. The paper illustrates a lightweight value visualization tool, running on top of existing CAD systems, to support the visualization of the life cycle value contribution of a given part or assembly. An early mock-up of the tool was developed for demonstration purposes and applied to a real aircraft engine component to verify the feasibility of the approach.

Relation to the thesis
The work leading to Paper B has driven the thesis work by identifying the challenge of visualizing value information to enhance decision making during the design process. The paper summarized the need for value and knowledge maturity communication, emerging from the descriptive study while proposing a prescriptive approach for value communication in gate meetings. The paper also served as a means for disseminating the idea of visualizing value contribution in CAD models, raising the interest of the community and serving as a relevant source of feedback and input for the enhancement of value recognition in the PSS design.

Author’s contribution
Ola Isaksson first provided the idea of linking value with CAD models during an informal discussion. The author was responsible for the explorative work and literature analysis work as well as most of the writing. The feasibility of the approach and the analysis of what and how to visualize was conducted by Marco Bertoni and the author. Marco Bertoni also contributed by writing some parts of the paper. Ola Isaksson continuously contributed with feedback and expertise.
Award
The paper was awarded with the Best-Paper-Award “The Service Lion,” at the 3rd CIRP conference on Industrial Product Service Systems.

4.3 Paper C

Summary
The paper proposes a conceptual scenario, described in terms of activities, inputs, outputs, actors, and mechanisms, which details how design concepts at the component level can be developed and assessed with a focus on their value contribution at system level. The scenario is mapped against the Stage-Gate process and highlights how the design activity needs to be complemented when introducing value as a main measurement criterion in an early stage. Furthermore, the paper describes an approach to communicate the life cycle value contribution of design solutions directly through 3D CAD models as a means to enable more value-driven, life cycle-oriented decisions during conceptual development.

Relation to the thesis
Through the proposal of a conceptual scenario, Paper C analyzes in detail how a value assessment activity and subsequent visualization can be applied in a real development project. The work identifies the actors and stakeholders involved in the value-driven process, introducing the value analyst as a key player possessing a wide knowledge and a deep understanding of the dynamics of the product within the overall system and along its life cycle. The work studied the integration and the correlation of value assessment, value visualization, and knowledge maturity assessment in a unique proposed approach toward a more value-driven process.

Author’s contribution
The author wrote part of the text and contributed to defining the paper structure. The author also contributed to writing the scenario description and describing the value visualization part, while Christian Johansson contributed to the knowledge maturity section. Marco Bertoni wrote the majority of the text process and conducted a final review of the paper. Both Christian Johansson and the author contributed to the language improvement and review of the text.
5 Value Assessment Capabilities in Early PSS Development

This chapter summarizes the results of the work. It covers two main areas of results: The first part focuses on how to support the assessment of the value contribution starting from the analysis of the As-Is situation; while the second part presents value visualization in CAD software as an approach to communicate the value contribution in early development stages.

The aerospace industry is characterized by a long and complex product development process that leads to the delivery of products via a usage phase that may last from 20 to 40 years. It can also be observed that, once a platform is developed and certified, passing through an expensive and critical stage, its derivatives and variants can reuse some of the original certificates for decades. Some examples include the CF6-80 aircraft engine developed during the 1970s by General Electric, whose derivatives are still in production (GE, n.d.), as well as the engine developed for the Boeing 747 during the 1960s, which is no longer produced but whose core technology is still found in the equivalent and new engine of the modern version of the B747, the B747-800 (Boeing, n.d. 1).

A fairly long development process complements such a long usage phase. Aerospace is a conservative industry, and new technologies are implemented only after a long and accurate development process. Design and development lead time may vary according to the functionality, criticality, and investment required for each product. The pre-development phase, involving research and development and market analysis, can last as much as 10 to 20 years, while what is commonly referred as product development takes from 3 to 5 years.

This happens because of the large investments needed to develop and produce products compared to other industries. Moreover competition forces developers to place products on the market with competitive prices, e.g. with the use of discounts, as much as 70% off the list price of an aero engine (Buxton, 2006), and thus earning the main profit on after market activities (i.e. maintenance, repair and overhaul). This implies longer payback times, sometimes as long as 10 years before cash flow from customers equals spending on development (Buxton, 2006).

The recent development project of a large commercial aircraft, the Airbus A380 (Airbus, n.d. 2), is a clear example of the complexity achieved by aircraft development programs. The A380 was defined by a set of more than one million drawings—much more than the number of drawings of the A340—and its architecture was broken down into approximately 70 major systems, leading to
Value Assessment Capabilities in Early PSS Development

several hundreds of pieces of equipment (Pardessus, 2004).

A new aircraft design is distilled from the knowledge and experiences of thousands of people from design, manufacturing, assembly, maintenance, etc., pointing to the integration of new technologies at the aircraft, engine, and subsystem levels.

Given these challenges, companies are preferring to team up in partnerships with each other to manage the risks, investments and skill challenges (Prêncipe, 2004), and sign risk and revenue sharing agreements. This has led to the necessity for the aerospace companies to think in term of extended enterprise (EE), terms often used to refer to the closer collaboration and co-ordination of co-operating independent companies among the whole supply chain (Jagdev, 1998).

System engineering (Schleger, 1956) and requirement engineering (Kotonya, 1997) are commonly adopted approaches to drive the product development process. Starting with the identification of customers’ needs, the aircraft manufacturer defines a list of technical requirements that cascade down to engine and subsystem manufacturers (Paper C). Technical requirements are the instruments through which the aircraft manufacturer communicates its requests to the extended enterprise, which is mostly happening when the contract with the supplier is signed (Paper A).

However, the focus on reducing lead time and costs does not allow suppliers to start their development activities only when the contracts are signed. Aerospace components development is incredibly time consuming as deep studies and accurate tests need to be performed. In order to grant short delivery time, and therefore shorter time to market for the aircraft, companies in the EE need to start their development effort much earlier than when they sign the contracts—namely, long before the requirements are shared. This exposes supplier companies to the risk of investing resources in developing a solution that will not fit the future requirements, causing them to invest additional money and resources in costly redesign activities (Paper B).

Being able to reduce as much as possible later redesign activities, and to reduce the effort and resources spent on developing solution not fitting requirements, is therefore a key challenge for aircraft sub-system manufacturer. From this perspective, understanding early in the design process what aspects of the future aircraft offer will bring more value to the final customer, will enhance the design process, driving concepts selection toward a system optimization, and reducing costs and time generated by not value adding activities.

5.1 From Requirements-Compliant to Value-Adding Designs

The request for the development of a new component most commonly comes from customers. For instance the request for developing a new component for an aircraft engine comes from an engine manufacturer, and it is formalized through the requirements stated in the contracts, together with the statements of work and the related engineering documentation. Hence, nowadays the development and selection of sub-systems/components concepts are primarily guided by requirements defined in contractual agreements (Paper C).
The requirements at the engine level cascade down to the sub-system level and are translated into more detailed requirements in terms, for instance, of loads, temperature, and geometry (Paper C). Figure 7 represents the requirement flow-down process along the supply chain. On one side, the requirements are cascaded down to the engine and sub-system suppliers, that use this information to improve and deliver their products by deeply focusing on providing designs that fulfill the requirements (i.e., to provide designs that are "requirements-compliant" to the greatest extent possible).

![Figure 7: Simplified requirements flow in the aerospace industry.](image)

In the bottom right of Figure 7, component manufacturers have internal technology development processes, driven by internal needs and a vision of a solution that can meet the needs (Högman, 2001). However, the "need" is often not crystal clear beforehand, given that the requirements are dependent on the engine configuration being defined. A series of iterative design activities, exploring the new technologies and their potential, are usually conducted, and experimentation and learning are emphasized during the early stages.

The common approach of cascading technical requirements from the top to the bottom of the supply chain makes it cumbersome for the sub-system manufacturer to broaden its innovation scope and proactively participate in radical innovation changes. For instance, an engine component manufacturer signing a contract stating a list of detailed requirements will target local optimal design, innovating the existing product incrementally. More radical solutions will most likely be neglected since they are not fulfilling the negotiated requirements. The paradox is that they could sometimes enhance the overall performances of other components, eventually having a positive impact on the overall system (engine or aircraft) (Paper C). In a nutshell, having a component optimized locally
does not ensure that the system (i.e., the aircraft) will be optimized globally.

This suggests the need to couple the requirements information with more qualitative information, such as overall context, design intent, and tacit needs, to better understand the overall value of a solution for the different levels of stakeholders. This information might take the form of value dimensions or drivers that, by complementing the requirements, enable a better management and judgment of their importance (Paper C). In this way, new design solutions at the component level could be judged not only by the local physical performances, but also by considering the value provided to the engine or to the aircraft in terms of enabling functionalities, enhancing overall performances, or impacting customer-perceived value. Using value as decision criteria design selection would point toward the more valuable solution from a system and lifecycle point of view, enabling incremental and radical innovation to be evaluated in the light of satisfying needs related to areas scarcely considered in the traditional component development as, for instance, servicing or maintainability (Paper A).

The shift toward providing more value-added design compared to requirements-compliant design is summarized in Figure 8, where the double stream of information (i.e., requirements and value drivers) flow from the top of the supply chain to the component manufacturer and, contrary to requirements-compliant designs, and value-added designs flow from the bottom to the top.

Figure 8: Requirements and Value related information flow in the aerospace Extended Enterprise.
5.2 The Value Assessment Process

An outcome of this study is the development of a conceptual scenario aiming to support the design teams in making more value-conscious decisions (Paper C). Figure 9 shows the set of activities, the actors and the related documentation that characterize the scenario, mapping it on the Stage-Gate® process adapted from Cooper (Cooper, 2001).

![Figure 9: Scenario phases mapped into the Stage-Gate® (Cooper2001) process model.]

Value drivers are defined from six generic lifecycle-oriented value dimensions, intended as generic value parameters applicable to products of different kinds. These dimensions have been identified and developed together with the industrial partners to capture the main value aspects to be addressed by aerospace projects. Examples of value dimensions have been provided by Bertoni (2011) and include Performance attributes, Risk, Profitability, Operational Performances, Illities (i.e., Survivability, Adaptability, Flexibility, Scalability, Versatility, Modifiability) and Intangibles.

The project leader and the managers, supported by the value analyst, specify each dimension into drivers, which are more product-specific and directly related to the component under development. Given, for instance, a value dimension such as Profitability, the team might define machine commonality as a relevant driver, which might be further cascaded down to criteria such as: percentage of reuse of existing turning machines. Similarly, the value contribution in terms of Operational Performances of two Intermediate Compressor Cade (IMC) concepts, might be evaluated using availability as a driver and Mean Time Between Maintenance, Mean Time Between Failure, etc., as criteria.

Some aspects of the product lifecycle may be more important than others, so the team has to assign weights at the different hierarchical evaluation level, i.e., value dimensions, value drivers, and eventually criteria. The weights and the final value scales are reviewed by the stakeholders and accepted by the management,
which sets the expectations for the next gate meeting. After the work is initiated, the project leader communicates expectations (scales definitions and targets) to the project team. If necessary, the project leader assigns resources, such as, additional expertise or additional manpower, to meet the targets as closely as possible (Paper C).

5.3 Assessing the Value Contribution of Alternative Designs

The empirical study demonstrated the need to carefully balance the information communicated from the value assessment to prevent engineers from being overwhelmed by information, while also taking care not to limit the effect of the approach by having an overly limited set of value dimensions to reason upon. Data collection has also shown that having 5 or 6 main value dimensions may be as effective as having 200 value dimensions because, in the first case, the limited number would cause the neglect of important aspects while, in the second case, only a limited part of the 200 values will be realistically taken into consideration. Meanwhile, having 25 to 30 value dimensions able to summarize the multifaceted value aspects of a design alternative may result in a good balance between synthesis and completeness. Furthermore, stakeholders have expressed a preference toward having single scalars as a result from the value dimension assessment and to be able to access the information they need in a lightweight format.

Having a product baseline as a reference and a target is especially important when dealing with value dimensions that are qualitatively assessed, thereby relating to “soft” aspects that are difficult to express otherwise. For instance, considering a value dimension related to the weight of a component, it might be relatively easy for an experienced engineer to understand the value of reducing the total weight by one kilogram; however, it might not be possible to easily understand the effectiveness of this change related to the increased commonality with other components or to the adaptability of the component in different engine settings. This sort of information cannot be translated in absolute terms, but needs to be communicated in relative terms, indicating how much a solution is better—or worse—than previous options.

More than the absolute value score, engineers and designers need to understand how a concept is positioned against benchmarks, determining the baseline (such as the actual product performances) and the target (such as the specification of a vision emerging from long-term forecasts). In order to make it possible for engineers to compare different value dimensions and enhance the tradeoff analysis, it is important that the results of the value assessment are shared in a common format, cleaned from any unit of measurement. Mimicking the scoring system used for the assessment of the Technology Readiness Level (Mankins, 1995), a 9-point scoring system is assigned to each value dimension and related value drivers. Therefore, the benchmark solution is used to set the baseline and the target value on a 9-point scale (Paper B). More in detail the scoring system is organized as described in the following list.
• Designs radically below the baseline (1, 2), no-go areas: Engineers are asked to rethink the concept and modify the component/system, even radically, if the result is significantly below the baseline (1). Based on the criticality of the driver/dimension, this result 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 other, more important dimensions to be improved.

• Designs close to the baseline (3, 4), rework area: Engineers realize that the new solution satisfies at least the performance that the existing products deliver. Engineers need to focus more on product improvement as the solution as-is will not generate any innovation. Although the score highlights that basically no improvement in the performance has been achieved, this score might be considered satisfactory for the engineers if the criticality is low and major improvements have been adopted in more important dimensions. When such values are for dimensions that are critical for the product and time and money for the rework activity are limited, this score may also lead to the decision to kill the development of the design.

• Designs better than the baseline (5, 6, 7), go areas: Engineers have positive feedback on the design they are developing as the score highlights that the design is moving in the right direction, although some refinement can still be made in order to achieve even better performance.

• Designs that fit the target or are better than the target (8, 9), go areas: Engineers can deliberate with good confidence on the value of the concept; the target has been achieved, and the dimension/driver may have even better performance than what was originally desired. The “over-the-target” dimensions are the ones where engineers are invited to study the tradeoff with other lower-performing dimensions, being free to decrease the value of the first in order to increase the value of the latter.

More specifically, the baseline level of a value dimension or driver is set to a score equal to 3; results of the value assessment that fall below this threshold (i.e., scored 1 or 2) indicate that the performance achieved by the new solution is inferior to the one used as a benchmark. Meanwhile, the target level is set to 8; thus, dimensions and drivers scored as 9 are considered to be better in performance compared to what was considered as the best desirable performance for the forthcoming solution.

5.3.1 Assessing the Knowledge Maturity of Alternative Designs

Contextual knowledge (Naveiro 2001) is often dispersed throughout different functions. It is tacit and related to people’s experience and expertise, meaning it is poorly validated and difficult to access. Furthermore, a main issue in the preliminary design phase of a PSS is that decisions have to be based on data that are both quantitative and qualitative—thus, made by assumptions and
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forecasts—as a historical series of data as reference may be missing. Decision makers require deeper understanding of the status of the knowledge at the gate to be able to answer questions such as:

- What is the reliability of the presented information? Does it reflect assumptions or verified facts?
- Is the information current or out of date?
- Are there specific knowledge assets that would need further development to contribute to the objective more clearly?
- Is there a need to prioritize refinement of some aspects over others?

Enabling designers to answer these questions is a first step toward increasing decision makers’ confidence in the tradeoffs they need to make. Thus, assessing the knowledge maturity before making a decision is a key step toward the selection of the most value-intensive PSS alternative.

For instance, a preliminary analysis result concerning the heat tolerance of an aero engine component may be sufficient in the feasibility stage of component design, whereas the same numbers may be too inaccurate to be valuable in the detailed design stage. The knowledge maturity assessment represents a valuable approach enabling companies to make more conscious decisions during early design, thereby ensuring that implicit assumptions, ingrained views, and provisional results related to value contribution are not mistaken for verified facts (Paper B).

The knowledge maturity assessment is seen as a complementary activity to the value assessment. The data gathered in a preliminary design phase suffer from poor maturity and reliability. It is particularly important, therefore, to have pointers that can help indicate at which level people may trust the material entering in the value assessment activity. In a hypothetical scenario, for instance, from the value assessment results it may appear that a new composite material could provide higher value in terms of reducing specific fuel consumption (SFC), and reducing maintenance time. However while the impact on SFC could probably be evaluated with a good reliability, using simulation models, the calculation and estimation of maintenance time could be affected by personal assumptions, or more or less consolidated experience of company specialists, thus the reliability of the information needs to be somehow evaluated.

5.4 The Value Visualization Approach

The development of value assessment capabilities, through the assessment of value and knowledge maturity during the design process, may be useless if not coupled with an appropriate strategy to communicate the results to engineers, managers, and designers involved in the design process. Existing literature focuses on the visualization of value-related information, underscoring how the visualization of value is a broad concept encompassing not only the perspective of the existing customers, but also other customers in the extended business network and the internal organization (Kowalkowski, 2009).
The visualization of value often implies the communication of intangible aspects that are difficult to understand due to the lack of experience in treating offers integrating service-related aspects (Kowalkowski, 2009). Therefore, the concept of value encompasses dimensions that are hard to measure and compare, meaning communication needs to enhance designers’ understanding by:

- Highlighting go and no-go areas as well as areas that necessitate a deeper study;
- Visualizing the patterns of behavior to the expert eye; and
- Visualizing the value in relative terms (i.e., comparing the design against a product baseline or a target).

Linked to the engineers’ necessity of knowing how much the outcome of the value assessment shall be trusted, the need to communicate knowledge maturity together with value-related information has been identified as a key feature for enabling an effective use of the information to guide decision making. A value visualization approach has been proposed to cope with this need while simultaneously more readily linking the value information with the object (feature, part, or assembly) manipulated by the designer (Paper B).

In the specific area of Computer Aided Design, color-coded CAD models have been extensively used to display the outcome of heterogeneous kinds of simulations, such as cost calculations, mechanical and electromechanical simulations, tooling and fixture design, and engineering process management (Gallagher, 1999; LMS, 2012; Zhu, 2006). The proposed visualization approach named LIVERY (Lightweight ValuE visualizatoR) is intended as practical decision support for PSS development to increase decision makers’ awareness of the value associated with a PSS design solution by visualizing value-related information as colored features in the product/component CAD model (Paper B). Given a feature, part, or assembly, the idea is to represent the outcome of the value assessment using color-coding (i.e., associating each feature, part, or assembly to a color), ranging from red (lowest value contribution) to green (highest value contribution), representing the relative distance with the baseline and the target.

Knowledge maturity is visualized through a superimposed transparency layer on the CAD model in order to provide visual feedback about the reliability of the knowledge used in the assessment (Paper B). The knowledge maturity scale proposed by Johansson (2009) is considered to be the most suitable for the LIVERY approach as it was developed in an environment—namely, the aerospace industry—that perfectly fits with the one studied in this research.

The combination of the five levels of knowledge maturity with the nine possible relative value scores results in 45 different combinations. Thus far, a component visualized with a clear shape and bright color communicates that the knowledge used to build the value assessment is tested and proven, thereby indicating that the assessment is reliable. On the contrary, a poorly defined figure with weakened colors indicates that the knowledge used for the value assessment is characterized by instability. Figure 10 shows the 45 possible combinations of
the visualization, using the impact of a new component on the fuel efficiency of an aircraft as an example.

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<tr>
<th>Knowledge Maturity</th>
<th>Fuel efficiency maximized</th>
<th>Fuel efficiency strongly improved</th>
<th>Fuel efficiency improved</th>
<th>Fuel efficiency slightly improved</th>
<th>Fuel efficiency slightly worsened</th>
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Figure 10: Colour scale and knowledge maturity transparency layer.

5.4.1 Implementation and Testing of the Approach

The LIVERY mock-up was realized using Siemens UGS NX® software. The results of a simple value analysis, performed in the MS Office environment, were exported in NX and automatically hued after converting the input file into a common .txt file. The development of a new technology for an Intermediate Compressor Case (IMC) for turbojet or turbofan engines was selected as a relevant industrial scenario for the testing of the approach. The IMC is one of the
biggest components of the engine and plays a key role from both a structural and a functional perspective. The data used for the value computation are entirely fictitious, and the example is provided only for demonstration purposes.

Figure 11 schematically represents the visualization approach applied to two alternative IMC concepts, named A and B. The approach aims to visualize the value contribution of the design alternative against the six main value dimensions described in section 5.2.

Figure 11: Example of components value visualization during trade-off analysis.

The overall value contribution is computed in the form of a single scalar on a scale from 1 to 9, where level 3 represents the baseline and level 8 is the target for each value dimension. Different colors help designers understand which are the value-intensive parts and where improvement should focus. Engineers can, therefore, compare two design alternatives (e.g., concept B – Figure 11) and visualize their value contributions across the given dimension. Each of the six main dimensions has to be considered the result of a merging of lower-level value drivers, which detail value gains and losses for each alternative design. The value for each value driver is computed by accessing a heterogeneous set of models (Paper B).

The simultaneous visualization allows for quickly analyzing design alternatives from different perspective that are usually hard to measure and compare. For example, in Figure 11, concept B would be preferable based on merely looking at performance attributes; however, the evaluation changes when taking the entire picture into consideration. Concept A, in fact, shows better characteristics in terms of profitability (cash flows), possibility to upgrade the solution to address changing environmental conditions (ilities), and intangibles. Moreover, the value computation is based on knowledge that is more mature. Similar reasoning can be driven by the analysis and comparison of other value dimensions (Paper B).

Figure 12 shows an example of how the color-coding approach can be implemented to evaluate the impact in terms of the logistics of the new engine component (visualized in grey) at both the engine and aircraft level.
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For instance, a new IMC configuration could have a major value because it allows the engine to be lighter or more efficient or requires less maintainability during the life cycle. This could affect the whole aircraft design, allowing for a different mounting system or a different wing shape. Alternative IMC concepts could have radical or minor impacts on the engine and aircraft structure. The lightweight visualization aims to raise the awareness about system-level impacts and supports a more intuitive comparison of different product/service solution alternatives (Paper B).

Figure 12: Visualization of the impact of a new component (grey) on engine and aircraft logistics.

Figure 13: Pictorial representation of the LIVERY mock-up.
Figure 13 depicts a pictorial representation of the value visualization interface on the CAD environment. On left-hand side, the results of different value dimensions assessment are visualized by the use of different colors, while the unique color on the bigger component on the right-hand side is generated by the weighted average of all value dimensions scores, thereby summarizing the value of a solution in a unique representation.

5.5 Evaluation of Color Coding Approach

The color-coding approach has gone through a series of evaluation and refining activities focusing on measuring the effectiveness of color-coded CAD models as decision-making enablers and studying its most suitable application in a real company environment.

In the first stage, an evaluation activity was conducted through the interaction with project partners; the approach was presented and discussed during two physical meetings involving three major aerospace manufacturers and experts representative of companies specialized in IT solutions. The approach collected positive feedback and was refined, leading to the publication of Paper B, which was recognized as the best paper at the 3rd CIRP conference on Industrial Product Service Systems. The approach was then subject of a dedicated webinar available to a wider set project partners, receiving both oral and written evaluation from attendees. Further meetings were held with PLM software providers to explore the possibility of the physical implementation of the approach in commercial software.
6 Conclusions

The conclusion chapter begins by revisiting the aim of the thesis, and further summarizes the results in relation with the initial research questions. Finally interesting areas for future research are discussed.

The design of a product is characterized by complexity, tradeoff, and uncertainty, which are sharpened in a PSS scenario by the addition of servicing aspects poorly considered in traditional product design. In early design stages, engineers possess less mature information about the forthcoming product and undertake studies with the purpose of understanding and defining what to develop.

This thesis has investigated how the decision making process in early stages of aircraft product development can be improved, by enhancing the awareness of engineers and designers about the value contribution of different design alternatives.

Starting from the analysis of the As-Is situation the thesis has identified issues and challenges in aerospace design, underscoring the need to make the design activity more collaborative and value driven. The research has identified the need to communicate expectations, needs, and value to the engineers in a more effective way, thereby enhancing their awareness about the value that changing a part could bring to a complex product.

Adopting a qualitative research approach through action research, this thesis has investigated, in more detail the aerospace industry, thus studying the early design stages of a conservative and capital-intensive industry where development processes last for about two decades and the use phase of a product may be of 30 to 40 years.

The thesis further proposed methods and tools for value assessment and value visualization focused on the adoption of a value driven perspective during the early design stages of PSS.

The work has lead to the following conclusions:

1) The results of the assessment of value and knowledge maturity during early design stages need to complement requirements information available to the engineers.

The local optimization of a component does not ensure that the system will consequently be optimized globally. Coupling the existing requirements information with value-related information, radically new technical solutions at
the component level can be compared and evaluated with a focus on the global value provision and not just on the local performance optimization.

2) **Value visualization through color-coded CAD models is a candidate technological enabler for communicating the outcomes of a value simulation,**

An approach aiming to the physical implementation of this feature is proposed. Interviews and informal conversations have shown that engineers and technicians prefer a representation of value that seamlessly integrates with the environment they are familiar with (i.e. CAD). Today, laboratory experiments with groups of students are in place to better test and evaluate this finding. The value needs to be visualized in a “lightweight” fashion, encompassing a complete but limited set of key value dimensions. The color coding approach allows for communication and benchmarking across dimensions that are difficult to measure and compare, this is achieved in a qualitative and comparative way, as quantitative information is rarely available in early design stage. To face the information reliability problem a knowledge maturity visualization is coupled with the value visualization, in order to allow engineers to make more accurate tradeoffs analysis of the design concepts.

The assessment and communication of value addition also raises additional issues that are not extensively treated in this thesis. Assessing and visualizing the overall value contribution of a component in a PSS scenario requires the sharing of models and data among companies, thereby enhancing enterprise collaboration capabilities. How to set up a system for sharing data or result from companies models while protecting private or critical information, is currently into study. Furthermore in order for the visualization to be effective, models need to be maintained and updated during the product life cycle by all the companies involved. Who should be the owner of the approach, and how the models should be maintained is still subject of research.

### 6.1 Future Work

Further work is needed to make the process of assessing and communicating value addition more transparent and robust. The definition of reliable value models to enhance the value assessment process is currently subject of research. Further work is also needed to implement systems to support value calculation and visualization.

Additional research is needed to understand the applicability of the approach in different contexts (e.g., automotive or naval fields) in order to drive changes and modifications that could lead to an increased generalizability of the findings.

To date, a number of semi-structured interviews have been conducted with product development specialists at an aerospace component manufacturing company to inspect the potentiality of the approach and how this would impact the everyday working activity. Specifically, the interviews were conducted with engineers and designers employed in different roles in the organization (i.e., a company senior specialist, a design team leader, and a designer engineer).
To evaluate the impact of color-coded CAD models in decision-making meetings, a set of experiments was conducted and is planned in an academic environment, involving both product development experts and master students. Results from these experiments will be available in late spring 2012. Future successful validation in a real company environment will require accessing engine and aircraft simplified performance models as well as experts at the engine and aircraft level.

Another emerging field for research is how information from PSS value models can be used in design and how PSS business model, mostly developed in marketing, can be integrated to enhance the comparison between PSS offerings and traditional product offerings. Hence, future research should focus on the following topics:

- How to better integrate PSS value models and PSS business models to enhance cross-functional value assessment capabilities.
- How shared Value Models should be built and managed to enhance the value assessment capabilities in the Extended Enterprise.
- How product development performances will be affected by a more value oriented approach, e.g. measuring the gain in terms of lead-time reduction and quality improvement in the PSS offer.
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In Glocalized Solutions for Sustainability in Manufacturing; Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2-4, 2011.
Assessing the value of sub-system technologies including Life Cycle alternatives

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Abstract
Emerging from an industrial case study in the aerospace industry, the paper proposes an approach to evaluate sub-system technology concepts from a life cycle perspective. The approach is composed by 5 main phases that aims to drive product designers towards more value-oriented design decisions. It is shown how different life cycle alternatives, such as the selling of a Product-Service-System instead of a traditional product, deeply impact the value of design alternatives. The described approach has been developed in collaboration with industrial partners and represents a potential instrument to enhance value-driven product design.

Keywords:
Value Driven Design; Sub-System Technology; Life Cycle Engineering

1 INTRODUCTION
Making the correct choice in the preliminary design phase impacts the entire product life cycle in an order of magnitude that could span from making the product being a big success, to generating, instead, a total business failure [1]. This statement gains more and more relevance when the product is characterized by a long lifecycle, when the technology is highly capital-intensive and when later life cycle modifications imply huge expenditures in terms of money and labor. In the effort of being competitive in the globalized market, a common and intuitive strategy for companies is to cut costs while increasing structure efficiency [2]. However, this approach does not always lead to success. Cost competition does not ensure long-term value added, because of the real risk of engaging in a cost-based fight against market followers [3]. So far, what becomes a real target to any company who wants to lead, or keep on leading, the market, is to provide the highest value to the system in which the company is competing. This concept should be considered not only from the final product seller focusing on end user, but also by all those companies that are relevant business partners in the supply chain. Colopy [4] stated that a product to be successful should maximize the value generated for the customer and for the system; how the profit is then divided between companies is instead decided by the market. To do so it is necessary to adopt a wide vision of the system, understanding how some changes in the sub-system impact on system level. This process is of relevant difficulty, because it implies the acquisition of an enormous knowledge about how the system works, and it needs therefore collaboration from upper-level companies, those could be reluctant to share core information about strategies and future actions with other product stakeholders. Nevertheless, in some business contexts all major companies of the supply chain can be interested in sharing this information. That is the case, for instance, of business deal implying revenue sharing, or concerning products embedding top-level technologies.

2 MOTIVATION AND OBJECTIVES
The main objective of the paper is to propose an approach to evaluate sub-system technology concepts from a life cycle perspective. Emerging from a real example the development of an aircraft engine component, the paper illustrates how the traditional functionality-performance analysis can be complemented by a more value-oriented assessment to enable more lifecycle-oriented decisions in a conceptual phase. The final aim of the paper is to contribute to the ongoing discussion about methods and tools to be used, in the preliminary design phase, to assess the value associated to a design alternative, in order to provide useful instruments to help design teams in choosing the solution that maximizes the value for the system.

3 RESEARCH APPROACH
The approach emerges from the analysis of real industrial problems rather then from a theoretical investigation. The initial problem statement has been defined in collaboration with major European industrial and academic partners in the aerospace sector, and has been further refined by interacting with an aircraft engine sub-system components provider. The approach for value assessment has been defined through workshops, physical meetings, informal interviews and company site visits. Such findings have been further analyzed in view of theory; improvements and implications have been proposed using as a reference the scenario created together with the industrial partner.

4 DESIGN CONCEPTS ASSESSMENT IN A LIFE CYCLE PERSPECTIVE
In an ideal scenario, companies should always select design concepts able to increase the added value for their customers and stakeholders. Being able to calculate a priori, in a transparent and repeatable way, the value of a given solution is, however, not a straightforward process. As stated by Anderson and Narus [5] remarkably few firms have the knowledge and capability to actually
assess value and, by consequence, gain an equitable economic return for the value delivered to customers. This problem is further exacerbated when the product grows in complexity and when the development activity moves from a “system” to a “sub-system”, or even “component”, perspective. Here the need for a methodology that could help the design team in assessing the lifecycle value contribution of a concept becomes evident.

The concept of “value” radically change the way decisions are taken at all the levels of detail the design activity is conducted. The optimal design solution has not to be merely found at the intersection of the “Performance” and “Functionality” axes, rather a third dimension, encompassing the “life cycle option” perspective, as shown in Figure 1, should be considered. The adoption of a life cycle value creation perspective allows designers to judge different alternatives considering a more complete set of information that could lead to a more value-oriented choice.

5 LIFE CYCLE OPTIONS ANALYSIS: AN APPROACH

The conceptual approach elaborated for sub-system technologies value assessment is composed by 5 main steps or activities, Figure 2 describes the approach and links each activity to the most relevant actors and stakeholders involved. To define the approach, a large cross-functional network of product stakeholders was established. This allowed the decomposition of the original problem into sub-problems reflecting product needs and requirements.

5.1 Problem decomposition and requirements identification

The requirements gathering process is usually a very complex affair and can represent a major obstacle to successful system development. It is argued that one reason for development projects poor performance, or even failure, is the mismatch between what expressed by the customers and what specified by the developers in terms of system requirements, a mismatch triggered by the differences in the cultural background of both sides [8].

Problem decomposition and requirements identification are the first steps of the methodology. Value assessment represents a big challenge for every design team, and thinking of facing it in a unique solution could lead to the rise of a big set of problems that could affect the results reliability. It is therefore incorrect to consider it as a “unique box” to be solved; it is instead preferable to adopt a strategy of problem decomposition. [7]. Studies reveal that, analysis-synthesis-evaluation is a design method largely adopted and discussed in literature [8][9]. Analysis refers to the decomposition of the problem into sub-problems; synthesis refers to the recomposition of sub problems in different ways; and evaluation refers to the test of the performance of new structures/systems [8].

As described by Simon [9] designers tend to decompose ill-structured problems into several sub problems. Additionally stakeholders’ expressed expectation needs to be collected by the design team. Designers should then interpret and reformulate the information acquired, in order to redefine expectations and validate them in a second round with stakeholders.
Without losing the focus on expectations and adopting a life cycle perspective, the team should be able to translate the expectations into needs. A needs analysis should then be performed in order to highlight the conflicts between needs.

5.2 Value drivers definition

Once the problem has been decomposed and the relevant innovation topics have been defined, it is necessary to set a number of relevant and measurable value drivers for the value assessment. In order to facilitate both a quantitative and a qualitative evaluation, some value criteria are first identified. These represent the key fields on which the product directly or indirectly impacts. Each criteria clusters the value drivers that refer to the same field so to make easier the comparison between the different alternatives. To define coherent value drivers the team in charge of the activity needs to access to information regarding needs and requirements, defined in the previous step.

Moving from high-level value criteria [10], a cross-functional panel of expert is asked to formulate relevant value drivers for a given component under analysis. Value drivers are, in fact, specific instantiations of generic value criteria. The value drivers for a compressor blade, for instance, may significantly differ from those specified for an intermediate case, simply because they differ in terms of geometry, material, expected lifetime, etc., and because of different customer expectations.

A large number of stakeholders are involved in this part of the process. Product development and customers still plays a relevant role as in the requirements identification phase, but a wider vision on the system is needed. In order to avoid focusing too narrowly on the performance-functionality axes, members with knowledge from different backgrounds has to take part to the process. Introducing a system view on the future product, including in the decision team a wider set of stakeholders such as top management, marketing and production managers, could help to create a value assessment result more reliable. However team composed by heterogeneous actors with very different background could prove to be difficult to manage, since the members do not have a convergent perspective on this level of abstraction. Therefore there is the need of a figure that possesses knowledge about how the whole process works on a system level, having a deep understanding of the dynamics and of the knowledge generation sources that involve the product along all his life cycle. Hence the figure of the Value Analyst is introduced with the aim of providing a life cycle oriented perspective to the design team along all the product development process.

The process of defining value drivers can vary in different context; however experience and deep requirements analysis are fundamental instruments to help facing this activity, as far as focus groups and interviews are useful methodologies to reach the goal.

5.3 Concepts generation

The aim of conceptual design is to develop promising concepts. This requires generating a wide range of concepts, to prevent overlooking valuable concepts, and evaluating/selecting these soon enough, to restrict their number from getting too large to allow meaningful consideration. [11]

The new concepts can imply incremental improvement of existing products or radical innovation. In both case several methodologies are nowadays applied to enhance creativity and innovation in the design team. Some important examples, largely discussed in literature, that can differently be applied basing the choice on the final goal the design team wants to achieve. Brainstorming [12], is a group creativity technique designed to generate a large number of ideas for the solution of a problem, it is a valuable methodology when talking about radical innovation, it has the quality of enhancing creativity promoting the creation of a high number of ideas [13] that, however, could often fall outside the technological or practical constraint of a product. Introducing the Value Analyst in the process as a moderator in the brainstorming session could drive the team toward more value-oriented ideas. Delphi [14], is a structured interactive forecasting method which relies on a panel of experts and is performed anonymously in order to avoid bandwagon effect. It is a methodology oriented more on forecasting the future, and used for marketing and demand forecast analysis [15], so it is more suitable for concepts evaluation than for new concepts generation. TRIZ [16] is a problem solving, analysis and technology forecasting tool derived from the study of patterns of invention in the global patent literature [17]. TRIZ implies a structured approach on the problem providing general guidelines for system evolution but could be weak when focusing on detailed design. It focus on technological evolution not enhance a divergent value-oriented thinking. Focus groups [18] are interactive group setting where participants are free to talk with other group members. Organizing focus group allows the team to focus deeply on the problem, however it could limit creativity and create bandwagon effect among the group [19]. Focus groups are powerful methods if the discussion is well driven by moderator and if a collaborative spirit is spread among the group. The value analyst should play the moderator role keeping the attention of the group focused on the goal.

5.4 Concepts evaluation

The fourth step of the methodology is the concept evaluation. It represents a complex phase that can be structured as a process itself. During this phase is of primary importance the sharing of knowledge from the upper system levels. The project coordinator acts as a link between different stakeholders, both internal and external. Concept evaluation is the most critical phase in the methodology and has been addressed in detail in the Life cycle oriented concept evaluation process’ chapter.

5.5 Concept selection

Last phase is concept selection, intended as an iterative process that does not always output a dominant concept immediately after the evaluation. A design alternative could prove to be more valuable in a value dimension and show to be weak under another point of view. A multi attribute decision-making problem [20] arises every time we need to decide between different complex design solutions. Nevertheless, it is important that the decision team can access all the data resulting from the evaluation in an easy and readable form, in order to have a complete set of information to base the decision upon. For this reason the concept selection phase is strictly linked to the value visualization. An easy and quick visualization of the value contribution of a solution can help decision-making team in choosing the best solution in a limited period of time. The amount of data to be evaluated in fact could be massive, generating therefore confusion, make people unable to judge the different alternatives from a wide perspective. Current research efforts, in the value-driven design field, tend to focus on the development of a means to quickly visualize and evaluate one or more solutions in a rapid manner. [6]

6 LIFE CYCLE ORIENTED CONCEPT EVALUATION PROCESS

Assessing the value contribution of a solution is an activity that cannot be reduced to the mere cost and revenue calculation; it is instead a combination of quantitative and often qualitative studies, which results need to be weighted on the basis of qualitative forecast and expectations. In general, there is currently no way to talk about better or worse with respect to an ad hoc aggregate of components. What is required is a process or rule for comparing designs to highlight what is better.
Since a relevant part of the parameters cannot be evaluated in a coherent quantitative way, it is often better to recur to a qualitative evaluation based on the comparison between a baseline value, for example the minimum value requested by customer requirement, and a target value, that could represent the ideal parameter result. Considering the engine component example mentioned before, we fix a MTBF of 20000 hours and a weight of 70 kg as a baseline, and we fix at 50000 hours the targeted MTBF and 60 kilos the targeted weight we would assign a radically different value to the solutions.

Qualitative ranking comparison is therefore necessary to run the value assessment.

A second critical aspect in the concept evaluation is the ability of correctly weighing the value drivers, to obtain a reliable final result. Depending, for example, from product nature, market requests, market forecast and company’s objectives, some value drivers need to be considered more relevant than others. The weighting is obtained through the definition of a scale of values, e.g., form one to ten, or through a percentage estimation of the value drivers impact over the total product value.

The activity of weighting value drivers is a key step in the approach. It is basilar for a designer to know which characteristics, qualities, or performances, are critical. This is a phase where life cycle options play a crucial role. Different lifecycle perspective can deeply influence the relative importance of a value driver compared to another. Consider for example a traditional product selling structure, meaning that the product is sold in a unique solution, and a product/service system selling architecture, that implies keeping the ownership of the product along all its life, the two different company strategies hugely impact on product life cycle, creating the need to consider new value drivers, as well as different relative importance for the already existing drivers.

Figure 3 summarizes the process of concept evaluation highlighting activities, methodologies, actors and outputs.

The following paragraphs describe the four activities citing as a case study the evaluation of two different intermediate compressor cases (IMC) for aircraft engine. The evaluation took place considering two different life cycle perspectives, the traditional selling, and the selling of the Product/Service System (PSS) [21]. The case study involved a sub-system technology that needs to be integrated in the aircraft engine structure. Different selling strategies, and therefore different life cycle and ownership alternatives, for the aircraft engine, impact the value assessment in the IMC design phase.

**Figure 3: Concept evaluation process.**

**6.1 Costs and revenues analysis**

The evaluation of costs and revenues concerns the estimation of the economical performance of an investment. Different methodologies are proposed by literature and broadly applied in industry. Between the most used it is possible to cite cash flow analysis [22], net present value and adjusted present value [23], internal rate of return calculation [24] and break-even analysis [25]. These activities are almost completely in charge of finance departments and cost managers.

Most of the concepts concerning costs and revenues analysis have been stated fifty or more years ago, however these instruments are currently still in use in many companies. Recently more methodology, i.e., the Modified Dizay Method [26], have been introduced in order to weigh individual cash flows by the amount of time that those cash flows are held, or absent, from the portfolio. These analysis, even if still valuable, provides as an output a value related only to the financial performance of the product, ignoring all other aspects related to the value perspective, i.e., the results are calculated in term of money, related to a single product/investment and the phenomena related to the whole value generation for the company are not considered. On a value driven design perspective cost and revenue analysis is still necessary but cannot be considered sufficient for a value assessment.

Considering the case study the adoption of a selling + maintenance and service policy implied the consideration of additional variables, such as spare part cost per year, service start-up costs, disassembly costs, recycling costs, remanufacturing cost per unit, service logistic costs, maintenance costs.

**6.2 Risk Estimation**

Every new product or component implies a certain level of risk. A large number of risk categories and a conspicuous set of methodologies is discussed in literature to estimate risk in new product development. Walker [27] presents a lightweight approach to technical risk estimation through a probability impact analysis. Altman and Saunders [28] propose an approach for credit risk measurement built around a mortality risk framework. Bangia et al. [29] describe a methodology for modeling liquidity risk in correlation with market risk measurement and management. Research is also focusing on regulatory risk measurement, exploring how a change in the regulation impacts the decision of an investment. Manteghini and Scarpa for example [30] describes how regulatory constraints affect a firm’s investment choices when the firm has an option to delay investment. William [31] focuses on product development
An intangible value could be the relevance of the engineering solution in relation with the flexibility of the environment, in which it operates. Aspects to be taken into consideration are, for example, the degree of compatibility to the external environment and how much an unexpected modification impacts the product function. More undefined, but not less important value is the effect of a choice on brand acknowledgment or in new knowledge acquisition. These aspects cannot be immediately translated into tangible performance, but contribute to the generation of competitive advantage in the long run.

In the case study analysis, considering a PSS life cycle, aspect like new knowledge acquisition, continuous improvement enhancement, robustness to external constraint modification or brand acknowledgment, are important, and, by consequence, a big attention has been paid to them during the definition of value drivers weights.

7 CONCLUSION

The described approach represents a potential instrument to increase the awareness about requirements and value embedded in a design alternative.

In authors’ belief the adoption of such a process for assessing the value of sub-system technology would help companies to move a step forward a value-driven design, granting good economic performance in the long run. Companies able to correctly assess the value of their sub-technologies, considering the value they provide to the system, would in fact maximize the economic return on their investment.

The advantage of the proposed approach is to increase the knowledge about the real value provided to the system by a sub-system technology, and take advantage form this since the preliminary design phase. Traditional cost or performance analysis doesn’t possess such capability of looking to the value of a product from a system perspective.

The proposed methodology has been developed in collaboration with an industrial partner, acting as a components provider for aircraft engines. The approach has been validated through discussions and workshops together with other international partners in the aeronautic sector, collected positive and constructive feedback. It does not pretend to be exhaustive neither to offer a final solution to the problem. It is instead open to discussion, improvement, and future research both inside and outside the aeronautic field.

Due to the complexity of the problem and the conspicuous need of data, it is difficult to foresee a large-scale application of the methodology in the short term. However we believe that knowledge sharing and communication are the key words to allow this approach being more and more applied in companies. In addition, the creation of automatic updates form company’s database and models will mark a decisive improvement towards the automation of the process.

The authors are currently involved in studies aiming to capture, model and understand customers’ and stakeholders’ needs and expectations. Moreover some methodologies and tools to help teams making decision at a gate, as for example the LIVERY, Light Weight Visualizator, proposed by Bertoni [35], are currently object of research.

8 ACKNOWLEDGMENTS

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Communicating the Value of PSS Design Alternatives Using Color-Coded CAD Models
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Abstract
The paper proposes an approach to increase the decision makers’ awareness at the gate, when evaluating PSS design alternatives from a lifecycle and value oriented perspective. The paper illustrates a lightweight value visualization tool, running on top of existing CAD systems, supporting value visualization of a given part or assembly, thanks to color coding. Information from value assessment is in this way translated into visual features of the CAD 3D model. Despite the approach is still on a start-up phase, an early mock-up of the tool has been developed and applied to a real aircraft engine component, in order to verify the feasibility of the approach.

Keywords: Product/Service Systems; Color Coding Approach; Value Visualization

1 INTRODUCTION
In the aerospace business, a stage-gate approach\cite{1} is commonly used to facilitate projects from idea conception to product launch. The key components of the stage-gate process are the stages, a set of information-gathering activities, and the gates, where information is assessed and decisions are made. The role of the gate is to evaluate what has been done in the previous stage and to decide the way forward, what should be done and what resources should be allocated for the next stage\cite{2}.

Reviewers evaluate the information developed during the stage and matched against a number of criteria to make a decision both external, such as environment and commercial pressure, and internal, e.g., established processes, organizational structures or incentive policy, that are often determined by the company’s overall strategy\cite{3}. A range of strategies aims at supporting decision making at the gate, such as Technology Readiness Level (TRL)\cite{4}.

Engineers, however, are no longer solving the problems they used to solve. In the aerospace industry, for instance, the design of a new aircraft engine cannot merely be reduced to a pure technical activity, such as the stress calculation on the blades or on the intermediate case. Engineers are no longer dealing with “tame” problems only; rather have to pay increasingly attention to “wicked” problems\cite{5} as well, such as developing a “passenger-friendly” airplane\cite{6}.

Additionally, it can be observed a move towards extending traditional product-based offers to incorporate more intangible assets, i.e. software and services, taking on lifecycle responsibilities to secure the aftermarket and to satisfy increasingly sophisticated customer needs. Initiatives such as Functional Products\cite{7}, Product Service Systems (PSS)\cite{8} and Integrated Product Service Engineering\cite{9} highlight the opportunity to add value to users and stakeholders by providing a “function” instead of merely selling hardware.

The complexity of functional product implies that companies need not only to assess the readiness of technological components, but also need to develop a shared understanding from a wide set of disciplinary concerns and perspectives, and finally assess how each piece of information or knowledge contributes to the knowledge base used to make decisions. Early on in the aircraft and engine development process it is necessary to reason upon how to improve hardware, software and service to provide a more comfortable, timely, and entertaining flight experience. Although the decisions made at this stage should always add value to the solution space, it is a great challenge to effectively understand the impact on the overall system “value” of changing design variables at the micro-level. Determining the most value-adding alternative is not a straightforward process, thus there is a need for better guidance for design choices, a guidance that translates the desires of customers and business developers into terms that are immediately meaningful to PSS engineers.

The evaluation needs to be based on a different set of criteria, related to the different stakeholders and life cycle phases. Early in the development process, it should be possible to capture, model and communicate the value contribution of different technologies, and their impact on the super-system, in a clear and easily understandable way. Methods and tools are needed to gather, merge and present in a coherent and relevant way all the information coming from different contexts and environments, including application fields far from the direct knowledge of the design team background\cite{7}.

2 MOTIVATION AND OBJECTIVES
The research framework in which this work has been conducted aims at contributing to the achievement of the ACARE\cite{10} targets by changing the way product development is initiated in the aerospace industry, through the development of innovative mechanisms to 1) capture, model and understand customers’ and stakeholders’ needs and expectations, 2) to incorporate the value dimension into preliminary design and 3) to identify criteria affecting customer perceived value to be used in preliminary design studies evaluation.

The paper summarizes the outcomes of an explorative study.
conducted in the frame of a European research project in the aerospace domain. It proposes an approach to support decision making at the gate, by increasing the decision makers’ awareness about the life cycle value of a set of PSS alternatives. The paper illustrates a lightweight value visualization tool, running on top of existing CAD systems, to support the visualization of the life cycle value contribution of a given part or assembly. An early mock-up of the tool has been developed for demonstration purpose and applied to a real aircraft engine component to verify the feasibility of the approach.

3 RESEARCH APPROACH
The study has been performed in the frame of a European Commission’s research project within the FP7 programme. The research project has provided access to several aerospace companies (i.e. major aircraft, engine and sub-systems manufacturers and other companies with experience in aerospace development projects), which have contributed to the problem domain definition with their empirical data and expertise. The research approach adopted can be described as inductive [11], qualitative [12] and participatory [13]. The findings have emerged from the understanding of a real industrial problem that involves all the stakeholders of a product/service system life cycle. The work has been conducted through physical meetings and workshops involving both academic and industrial partners. Semi structured interviews, virtual workshops and company site visits represent the main data gathering activities. The data gathered have been further analyzed in view of theory; improvements and implications have been proposed using as a reference the scenario created together with industrial partners.

4 EARLY STAGE DECISION MAKING IN PSS DESIGN
In an ideal world, design teams would be able to deliver the best possible design calculating costs and benefits of everything they do beforehand. In the real world, however, rational decision making is a rare occurrence [14]. The design process paradox [15] highlights in fact that the more the team learns, the less freedom it has to use what it knows. Designers are in the unfortunate situation of having limited knowledge in the early stages, when they have good opportunities to influence the design, whereas when they have established a more developed knowledge base in the later stages, major decisions have already been made, capital has already been committed, and it is therefore more costly and time-consuming to make changes. This is particularly evident when developing products that target life cycle commitments. Approaching the development of functions, it is virtually impossible to know everything about all alternatives, and even to talk about what ‘best’ means: “there are no true or false answers. [...] solutions are expressed as ‘good’ or ‘bad’ or, more likely, as ‘better or worse’ or ‘satisfying’ or ‘good enough.’” [6].

Gut feelings and intuition play an important role in the decision making process [16] of PSS. Making a decision is often about settling for what is good enough rather than waiting for the optimal solution to emerge. One of the reasons is that the downstream implications of a PSS alternative is not very visible or well communicated at the gate. Especially when taking decisions about the future, life cycle issues tend to be neglected in favor of technical performances of the solution, i.e. better the physical characteristics of the product are, more likely the hardware will be considered for further design.

4.1 Value assessment at the gate
The novelty introduced by a PSS solution causes a radical change in the way the engineers for the team approach the decision-making problem. Traditional ‘hardware’ development, in fact, takes the move from a ‘static’ and well-defined product usage and from a clear understanding of the required capability. Such context is established by the customer and not generally subjected to significant evolution over the programme life. As opposite, the design of a PSS needs to consider a more service-oriented solution where companies “do not have the luxury of rigidity within their requirement definition” [3]. The initial requirements are subjected to changes in the use/operation phase in response of the changing environment.

Reasoning from a life cycle perspective, merging hardware, software and services, engineers have to deal with plenty of secondary impacts on design decisions that are difficult, if not impossible, to foresee and balance beforehand. Sometimes it is preferable to sacrifice some sub-system performances to optimize the overall system. For components that are going to be sold as PSS, and supported for 20, 30 or even 50 years, the decision making task at the gate should not merely focus on the readiness assessment of technological components. It should be oriented towards understanding the value contribution of a given solution in a much wider perspective, estimating the value contribution at super system level, as outlined by one of our informants in the aircraft engine components manufacturing business: “Nowadays you can easily tell why a solution is the optimal one in terms of performances, however it is not straightforward to see if it is optimal also from a value perspective. Hence, we have to look at people, tools, processes for developing the optimal solution both from a business as well as from a customer viewpoint.”

Nowadays the overall goodness of a solution is mainly expressed by technical performance figures and cost. There is a need to assess design solutions across a wider range of value-related dimensions, such as monetary value, perceived value, confidence on the product, and requirement fulfillment levels; those need to be represented in a more holistic value model. A main challenge, especially when working on cross-functional and cross-disciplinary teams, is to aggregate and communicate this value information in an easy and understandable way to enable quicker and more agreed design decisions.

4.2 Maturity assessment at the gate
In PSS development, there are many environmental and contextual variables, with varying degrees of controllability. While it would not be feasible to create innovative PSS and, at the same time, completely eliminate uncertainty and ambiguity, companies would most likely benefit from learning more about what exactly those uncertainties and ambiguities involve. Decision makers at the gate require a deeper understanding of the status of the knowledge base, to deal with uncertainty and ambiguity and to make more confident decisions. A crucial challenge is how to assess knowledge sources and knowledge assets with respect to their fitness-for-purpose. What is the level of readiness of the presented information? Is it reflecting assumptions or verified facts? Is there anything missing? Is the information current or out of date? Are there specific knowledge assets that would need further development to contribute more clearly to the objective? Is there a need to prioritize refinement of some aspects over others?

A key concept in the PSS decision making process is maturity, which is defined by Grebici et al. [17] as a compromise between the target uncertainty and the expected uncertainty, denoting maturity as the distance between the level of completeness relative to what
should be the level of completeness, i.e. as-is status versus to-be status. Knowledge maturity builds on the assertion that everything cannot be known – some things are known, while other things are not, i.e. some variables are exogenous and uncontrollable, and others can be controlled. It measures the state of the development of a piece of information with respect to achieving a purpose, which implies that a piece of information may be mature for one purpose and immature for another. For example, a preliminary analysis result, concerning the heat input to an engine component, of an aeroplane engine component, may be good enough in the feasibility stage of component design, whereas the same numbers may be too inaccurate to be valuable in the detailed design stage.

The knowledge maturity assessment may therefore represent a valuable approach for companies to take more conscious decisions at the gates, making sure that implicit assumptions, ingrained views and provisional results are not mistaken for verified facts. In these situations, there is a degree of uncertainty that needs to be handled, perhaps not by directly focusing on reducing the uncertainty, but by designing the decision makers in achieving a better understanding of what those uncertainties, ambiguities, and assumptions actually involve. Creating an increased awareness on the status of information and knowledge assets could allow companies to move forward with known risk, rather than making decisions based on unclear rationale.

5 THE INFLUENCE OF COLOR-CODED INPUTS ON DESIGN DECISIONS

The ground hypothesis for this study is that the use of multiple cues to encode information can enhance life cycle information processing at the gate, taking advantage of associative processing. Associative or peripheral processing, in fact, provides information quickly and automatically, decreasing time and effort needed to complete a task [18]. The theory of cue-summation proposes that multiple cues presented both across and within media/channels can improve information processing, mainly because these cues provide more opportunities for the learner to discern the new information being presented [19].

In the preliminary design phase of a PSS, the authors believe that color-coded 3D CAD representation might enable the combination and communication of heterogeneous information, when deciding upon the most suitable configuration of the hardware for the functional purpose (e.g. displaying the value of a solution across the different life cycle phases, communicating the impact of the solution at super-system level and showing the maturity of the knowledge used to compute the value model).

Color emerged as one of the key cues for this study for several reasons. The influence of color and graphical information presentation in a managerial decision environment is an argument discussed since the 70s. Colors have been found to be the most effective coding technique for aiding visual search [20], and properly used colors has been found to improve the usefulness of an information display system [21].

Further, Chute [22] stated that color’s ability to delineate figure-ground relationships, to show interrelatedness, and to make discrimination, underscores color’s effectiveness in learning. A later experiment conducted by Benbasat [22] showed that color has several beneficial effects for decision making. Subjects with color-coded reports managed to obtain a significantly higher average profit over the first 10 trials and completed the task using fewer trials. The processing of color, in fact precedes the processing of other attributes [24]. Further studies have highlighted the importance of colors as supplementary information cue in interfaces design to encourage associative processing [25].

In the specific area of Computer Aided Design, color-coded 3D models support several analyses such as cost calculation, mechanical and electromechanical simulation, tooling and fixture design and engineering process management. A multilayer color coding visualization, able to access the input data from the system and subsystem models and summarize them in a clear, understandable and useful way, can therefore represent a relevant instrument during design and re-design phases. The idea of the color visualization aims to help the choice of the designers thanks to the creation of a structure that allows the automatic visualization of the value generated by different design alternatives, from different life cycle points of view, in a unique representation in a CAD environment, trough a constant link to different product models.

6 LIVERY: THE LIGHTWEIGHT VALUE VISUALIZATOR

LIVERY (Lightweight ValueU visualizer@R) is intended as a practical decision support for PSS development to increase decision makers’ awareness of the life cycle value associated to a PSS design solution. LIVERY is organized in a multilayer visualization structure where at different level of detail, from component level to whole aircraft level, a different value visualization is associated. The color-coding visualization consists of two layers of representation, the first concerning the concept value, the second representing the knowledge maturity of the concept.

Value visualization consists in the association of a scale of colors, from green to red to each component/product. The value is related not only to the physical characteristics of the provided hardware, instead it aims to embed the value of the underlying service for a given hardware solution. The input data are qualitative or quantitative; each color is linked to a particular numerical value or range of values, which are the results of the aggregation of weighted values of underlying models. The different levels perspective allows the visualization of value intensive phases along the life cycle.

A main issue in the preliminary design phase of a PSS is that decisions have to be based on very qualitative data, assumptions and forecasts, since an historical series of data as reference is missing. A transparency layer is over-imposed to the 3D model to provide a visual feedback about the maturity of the knowledge used in the representation. The underlying value models can be generated from either qualitative or quantitative studies. Values can be the results of deep empirical analysis, easy measurable and defined, as well as they can be based on designers’ assumptions, panel of experts’ suggestions, or market forecasts, implying therefore either a qualitative or statistical nature. Hence, LIVERY aims to display the maturity readiness of the knowledge assets used to compute the value model, in order to take more conscious decisions at the gates, making sure that implicit assumptions, ingrained views and provisional results are not mistaken for verified facts.

7 APPLICATION EXAMPLE

The LIVERY mock-up has been applied to visualize the value contribution of two alternative intermediate compressor cases (IMC) for turbojet engines. The intermediate case structure includes a core structure, an outer ring, a mechanical connection between the two parts and, occasionally, integrated structural fan outlet guide vanes. Figure 1 shows where the IMC is located in the engine. The intermediate case supports the high-pressure bearing structure and a low-pressure bearing support structure that includes the thrust bearings. The forces that act on the bearing generally occur as a
result of aircraft manoeuvres and forces are typically g-forces, gyro momentum and other flight induced loads.

![Figure 1: Intermediate case (IMC) position in a jet engine.](image)

The IMC is a so-called “cold structure” since the operating temperature is considered to be fairly low compared to the parts downstream of the combustion chamber. This is also one of the reasons why the IMC is usually made of materials like titanium and aluminum. In the past the fan outlet guide vanes were mounted as separate parts between the fan rotor and the intermediate case. The current trend is however to integrate the vanes into the load carrying IMC-structure. Aerodynamically shaped guide vanes are used to redirect the flow from approximately a 35-degree swirl angle to axial flow.

From a product development perspective, several trends are currently affecting the design of this component. First, aircraft engines are getting larger in diameter to increase the bypass ratio and so needs the intercase. Secondly, aerodynamic functions are increasingly integrated with the intercase. Thirdly, the intercase needs to withstand higher temperatures and heavier loads, meanwhile reducing its weight. Eventually, the intercase is mounted on increasingly electrically powered aircrafts, so needs to provide room for attaching electrical equipments. In the example, two different intercase alternatives have been considered: 1) a casted titanium intercase and 2) a fabricated titanium+aluminum intercase with foam core hollow vanes.

The LIVERY mock-up has been realized using Siemens UGS NX® software. The results of a simple value analysis, performed in MS Office environment, have been exported in NX and automatically hued after converting the input file a common .txt file. The data used for the value computation are entirely fictitious and the example has only a demonstration purpose.

**Concept A**
- Casted titanium

**Concept B**
- Fabricated titanium/aluminum with foam core hollow vanes

![Figure 2: Concept A value contribution.](image)

Figure 2 represents a schematic way the visualization approach applied to concept A. The approach aims to visualize the value contribution of the design alternative against six main value dimensions, namely: Performance attributes, Risk, Profitability, Operational Performances, Iliities and Intangibles [26].

The overall value contribution is computed in form of a single scalar on a scale from 1 to 9, conceptually derived from TRL, where level 3 represent the baseline and level 8 the target for each value dimension. Different colors helps designers to understand which are the value intensive parts and where improvement should focus. Engineers can, therefore, compare two design alternatives (e.g. concept B – Figure 3) and visualize their value contribution across the given parameters.

![Figure 3: Concept B value contribution.](image)

Each of the 6 main dimensions has to be considered the result of a merging of lower level parameters, which detail value gains and losses for each alternative design. The value for each sub-parameter is computed by accessing a heterogeneous set of models.

In LIVERY, knowledge maturity assessment is seen as a complementary activity to the value assessment. The value models built in a preliminary design phase suffer from poor maturity and reliability of the data used. It is particularly important, therefore, to have pointers that can help indicate at which level people may trust the material entering in the value assessment activity. It is highly beneficial to understand the expected level of quality of the final output, i.e. correctness of the decision taken regarding the design solutions proposed at the gate. In order to calculate the maturity, LIVERY adopts the maturity calculation approach proposed by Johansson et al. [27], who have developed a knowledge maturity model to assess the state of readiness of a knowledge asset using a narrative scale. Knowledge maturity is computed over three dimensions: input, method (tool), and expertise (experience) on a scale from 1 to 5. Johansson [27] rank as 5 an Excellent knowledge maturity, meaning that content and rationale have been tested and proven and reflect a known confidence, that the procedure to produce the content and rationale reflects an approach where tried out methods are used, where workers continually reflect and improve and where lessons learned are recorded. Level 4 is defined as Good and level 3 as Acceptable. Knowledge maturity is Acceptable when content and rationale are more standardized, when there is a greater extent of detailing and definition and the procedure to produce the content and rationale is stable with an
element of standardization and repeatability. Level 2 is ranked Doubtous and level 1 as inferior. A knowledge maturity level ranked 1 means that the content and rationale is characterized by instability (e.g. poor/no understanding of knowledge base), the procedure to produce the content and rationale is dependant on individuals and formalized methods are non-existent. This enables an assessment of input data both of the tools to refine or develop the input into an output, and of the individuals contributing to the work. Furthermore it allows worldwide-located teams share an artifact around which they can identify and discuss issues of concern, visualize the current status of the knowledge base, and negotiate a shared understanding of the advantages and drawbacks with the available knowledge base. In a system-of-systems perspective, especially in business-to-business situation, it is also important how a given design alternative impacts on the value scale of the different levels of customers. Figure 4 shows a more detailed representation, visualizing the impact of Concept A and Concept B on engine and aircraft level.

![Concept A vs. B system level impact.](image)

A new intercase configuration could have a major value because it allows the engine to be lighter, or more efficient, or requires less maintainability during the life. This could generate consequences on the whole aircraft design allowing a different mounting system or a different wing shape. Alternative intercase concepts could have radical or minor impacts on the engine and on the aircraft structure. The lightweight visualization aims to raise the awareness about system level impacts and supports a more intuitive comparison of different product/service solution alternatives. Eventually, concept B would be preferable merely looking at performance attributes, but the evaluation changes when taking the all picture in consideration. Concept A, in fact, shows better characteristics in terms of profitability (cash flows), in terms of possibility to upgrade the solution to face changing environmental conditions, as well as in terms of Intangibles. Moreover, the value computation is based on knowledge that is more mature.

8 DISCUSSION

LIVERY is an approach that presents some relevant issues to be discussed. It provides the possibility to make a more intuitive visualization of life cycle value of a sub-system/component to be included in a functional offer. LIVERY is currently under implementation in a CAD environment, thus no formal evaluation has been performed yet. However the approach has been presented and discussed with several partners from the aerospace industry and has received positive feedbacks. The approach can help in communicating where the value is “hidden” in the product, increasing the awareness of decision makers about life cycle issues. The design team could visualize the impact in term of value of a decision with different system perspectives, choosing the activity layer of interest. Browsing through the different visualizations, the decision making team could understand sweet spots and weak spots of the alternatives. The development of visualization technologies needs to consider the problem of information overload. The target is to condense information to a minimum in order not to dump engineers and designers with too many inputs. It may also link service issues with the physical product and immediately relate the value associated to the service part to the hardware. The definition of the value metric can be ambiguous when revenue is not the main measure of the product. It might not be straightforward in many situations to summarize everything to a number representing the overall value associated to a given choice. An important aspect is also to define which criteria to be used for the value calculation, in the example the criteria proposed by Bertoni [28] have been considered, however different criteria could be related to different products in different application fields. Furthermore to grant the results consistency it is necessary to previously establish a baseline value level and a target value level; how baselines and targets should be set, related to the product considered, strongly depends from customers and management needs and requirements. On the same line is the definition of parameter weights, allowing prioritizing some variables instead of others during the value assessment phase.

This approach, even if discussed with different industrial partners, needs to be deeper analyzed and validated together with designers in a real product development process, in order to obtain more constructive feedbacks to improve the overall functionality. Two additional fields of study related to the topic, but outside the paper intent, are the analysis of how the process at the gate would really change after the adoption of LIVERY, and how and where the information treated can be retrieved.

9 CONCLUSIONS

In this paper an approach is proposed for communicating the value of different PSS design alternatives. In order to face with the multi attributes decision making problem, considering all the aspects related to value generation in a product/service system, the authors have developed and used a methodology aiming to consider both value, tangible or intangible, and knowledge maturity. The work led to the formulation of a coloring approach reflecting the value embedded in a PSS design alternative, linking this information to the concept knowledge maturity. To verify the feasibility of the idea, the functionality of the approach has then been implemented and tested in a CAD/PLM environment. Although the approach is still in a start-up phase, we believe that in the future this methodology could contribute to the design of a PSS solution, and we consider it enough advanced to be included in a value drive design assessment approach. Since the objective of the paper was to propose an approach, despite the possibility to access some real models and parameters, the example described uses fuzzy data in order to avoid private data secrecy problems.
Further developments will focus on correlated fields: first the refinement and testing of the mock-up in a laboratory environment with a selected set of engineers/designers actively involved in gate decisions activities; second, the extension of the system-impact layer to be able to visualize the alternatives’ impact at higher customers levels (i.e. airlines and the passengers), and third the evaluations of the implications for the product development process performances, i.e. measuring the gains in term of lead time reduction and quality improvement of the functional offer.

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TOWARDS ASSESSING THE VALUE OF AEROSPACE COMPONENTS: A CONCEPTUAL SCENARIO

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ABSTRACT
The development of complex products, characterized by long lifecycles and deep supply chains, requires enhanced capabilities to assess, in an early design stage, the value of a solution not merely from a requirements fulfilment perspective. The paper proposes a conceptual scenario, described in terms of activities, inputs, outputs, actors and mechanisms, which details how aircraft components can be developed and assessed with a focus on their value contribution at system level. Moreover, the paper proposes an approach to communicate the lifecycle value contribution of design solutions across a heterogeneous set of value dimensions, drivers and criteria, directly through 3D CAD models. The scenario, together with the methodological and technological tools enabling value assessment, has been created and preliminary validated together with major European aerospace manufacturers.

Keywords: Value driven design, Decision making, Knowledge maturity, Value visualization

1 INTRODUCTION
All designs are created for a purpose. When dealing with “tame” problems [1] only, such purpose is well mirrored by the product requirements, which often provide a good enough basis to identify the best of the available design alternatives. However, when paying increasing attention to “wicked” problems [1], the capability of a solution to add value to customers and stakeholders is more difficult to be assessed without explicitly linking the product features to the initial needs and expectations. In this context, measuring requirements satisfaction is no longer sufficient to assess the “goodness” of a design, therefore the technical product performances need to be complemented by more qualitative criteria to better understand the value of a solution from a system and lifecycle point of view.
When collaborating with several partners for the development of new products/services, the initial purpose is often lost when the requirements are cascaded down to suppliers and sub-contractors. Hence, the sub-system manufacturers tend to target local optimal designs minimizing the costs, rather than to comprehend how a radical innovative technology might add value to the overall system and to the different customer levels.
This issue is particularly evident in the commercial aerospace business. Comfort, timeliness, entertainment and environmental consciousness are emerging driving forces in new aircraft development programs [2][3]. On a more technical level, this demands for altered functions in the engines to improve the efficiency in energy use [4], which turns into new requirements for the engine sub-systems and components.
At component level, a good understanding of the intended use of the forthcoming solutions (i.e., of the purpose of the system) is crucial to realize the relative importance of derived requirements and, eventually, to make the right decisions on the technologies to be developed. Not communicating such purpose to the designers increases the possibility of generating sub-optimized solutions adding unnecessary risk and costs to the entire system. The development of value-assessment capabilities can support the sub-system manufacturers in better satisfying the “needs that matter”, avoiding large, expensive, and ultimately unsuccessful redesign cycles at all levels of development.

2 MOTIVATIONS AND OBJECTIVES
Nowadays, raising the designers’ awareness on the overall value delivered by radical innovative design solutions at component level is a major challenge for the aerospace sub-system manufacturers.
The concept of value is far more difficult to manage and communicate than technical- and cost – related information, and the knowledge used for calculating the value contribution of a solution is less intuitive to formalize, access, validate and share than other product properties [5].
This calls for a methodological and technological approach to simulate and communicate, in an objective and transparent way, the value contribution of alternative design options and technologies early in the product development process. The objective of the paper is to propose a conceptual scenario, described in terms of activities, inputs, outputs, actors and mechanisms, which details how design concepts at component level can be developed and assessed with a focus on their value contribution at system level. The scenario is mapped against the Stage-Gate® process developed by Cooper [6], and highlights how the design activity needs to be complemented when introducing value as main measurement criterion in an early stage. Furthermore, the paper describes an approach to communicate the lifecycle value contribution of design solutions directly through 3D CAD models, as a means to enable more value-driven, lifecycle-oriented, decisions during conceptual development.

3 METHODOLOGY
The research can be methodologically likened to action research, which is commonly described as a set of iterative activities performed jointly by practitioners and researchers [7]. The value assessment approach proposed has been developed within an European Commission’s Seventh Framework (FP7) Programme project, which has provided access to several aerospace companies (i.e., major aircrafts, engines and sub-systems manufacturers and other companies with experience in aerospace development projects).

Action research follows a particular diagnosis, invention and reflective learning cycles [8], which is aligned with how the authors have performed the research in the project. Empirical and qualitative data have been collected through the authors’ active participation in physical and virtual work-meetings with the industrial partners. The discussions with the aerospace companies in the diagnosis stage have contributed to the clarification of the problem domain, to the definition and validation of the scenario and to the development of the visualization approach. Reflective learning has been aided by the continuous participation in debriefing activities, held by the research team in relation to the work-meetings. The findings have been iteratively discussed and validated with the project partners, which have actively participated with their knowledge and expertise to the development of a preliminary mock-up for value assessment and visualization.

4 EMERGING DECISION-MAKING ASPECTS IN PRELIMINARY DESIGN
Stage-Gate® [6] is a common process in aerospace to guide the development projects from idea generation to product launch. The key components of the Stage-Gate® are the Stages, where information-gathering activities (summarized by deliverables) take place, and the Gates, where information is assessed and decisions are made.

As identified in previous research [9], the deliverables brought to the Gate meetings include summary documents, criteria documents, design rationale documents, technical reports, analysis results, and test reports, as well as the tacit knowledge of the people performing the work. Yet, the empirical study shows that value-related information is not reported at the gate in a clear, transparent manner, thus value-oriented decisions are difficult, because lacking of adequate supporting documentation.

4.1 Value Assessment
Considering that every system exists to deliver value to stakeholders [10], at the time of making a decision the analysts need to establish a link between the technical parameters and the customer value, in order to identify the best alternatives. As pointed out by one of our contacts in the aircraft engine manufacturing business, today the advantage of a solution is mainly expressed by technical performance figures and cost: “Nowadays you can easily tell why a solution is the optimal one in terms of performances, however it is not straightforward to see if it is optimal also from a value perspective. Hence, we have to look at people, tools, processes for developing the optimal solution both from a business as well as customer viewpoint”.

In spite of the centrality of the value concept, in literature there is a wide diversity of opinions and many speculative assertions on the real meaning of value, and on how decision makers should assess and trade-off design concepts against value-related criteria. Value Driven Design (VDD) [11], for instance, aims to enhance existing systems engineering methods by “introducing economics in the decision making process and enabling optimum solution strategies to be instantiated during the conceptual and preliminary design stages of a product”.

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VDD can be seen as an overall scoring system, feeding a vector of attributes (Extensive attributes) into a function (Value model) with the purpose of producing a scalar number (Surplus value) to rank a design. Surplus value is a surrogate object for profit, which may take the form of Net Present Value (NPV) when the product generates revenues over long periods. Extensive attributes are attributes of the system being designed, or of its components, such as all performance attributes, reliability, maintainability, safety, cost, schedule and technical risk.

For a system characterized by high costs, a long lifecycle, complex interdependencies between its components and dynamic operational contexts, value is also determined by the capability to maintain or improve the function in presence of change [12]. Tradespace exploration [13] considers customer value embedded in the customer process context and utilizes various “ilities” [14] (i.e., Survivability, Adaptability, Flexibility, Scalability, Versatility, Modifiability) as criteria to evaluate the system robustness under changing operational conditions. The “Epoch” framework proposed by Ross et al. [12] allows the systematic creation of trade-space models to quantify these “ilities”. Other valuation methodologies do exist (e.g., Real options for flexibility [15] [16]) but only for a few of these criteria. Furthermore, value is often intangible [17], perceived by the customer as an individual rather than objectively defined by a provider [18]. Goods and services can be arrayed on a continuum of relative tangibility, with goods being more tangible and services more intangible [19]. Intangibles are often associated with knowledge, emotions and experiences, dimensions that cannot be experienced by the customer before using the product. Steiner and Harmor [20] have proposed an extended model of customer value, which includes intangible criteria (such as epistemic emotional or image value) to be used for assessing the overall value of a system in the beginning of a product development project.

4.2 Knowledge Maturity

Making a decision is often about dealing with trade-offs among conflicting parameters. Trade-offs are more difficult to handle as uncertainties in the problem definition and in the knowledge base increase. Relevant value knowledge is typically dispersed across many different functions in the organizations, it is often poorly formalized and agreed, rarely readily available, and difficult to communicate in a structured manner, or instantiated as product characteristics [5]. Moreover, value knowledge is mostly tacit, poorly validated and difficult to readily associate with the product in question. This means that the decision makers need to know, when analysing a trade-off, if the figures provided in relation to a given value criteria are reliable, or are based on flawed or missing information [21] (e.g., placeholder values [22]), as well as on assumptions lacking of completeness, trustworthiness, or accuracy [23].

Raising the awareness of what such flaws entail is a first step towards increasing decision makers confidence in the trade-offs they need to make. From a value perspective, it is necessary to critically evaluate the status of the knowledge on which the value model is built. Some of the questions regarding how to assess the readiness of information or how actionable the value-related knowledge are: How much trust can be put in the quality of the information used for the value calculation? Are there any uncertainties? What assumptions have been made? Is there any information missing? Are there needs for further developments of knowledge assets to contribute more clearly to the objective? Is there tacit knowledge to complement (or perhaps challenge) the formal documentation and how well is it aligned?

In these situations, there is a degree of uncertainty that needs to be handled, perhaps not by directly focusing on reducing the uncertainty, but rather by assisting the decision makers in achieving a better understanding of what those uncertainties, ambiguities, and assumptions actually involve [24]. The concept of knowledge maturity [9] is therefore crucial as a practical decision support for value assessment. The objective is to support decision makers in the process of challenging value-related assumptions, of evaluating cause-and-effect relationships and of assessing the accuracy, quality, stability, completeness, and relevance of value-related knowledge at hand. Knowledge maturity can increase decision makers’ awareness of the knowledge base on which the value assessment is based and support cross-boundary discussions on the perceived maturity of available knowledge.

5 SCENARIO DEFINITION: VALUE ASSESSMENT OF AN IMC COMPONENT

In the future, aircraft engines are expected to become larger in diameter to increase the bypass flow, thus reducing fuel consumption and obtaining other desirable effects. Engines are also expected to support a More Electrical Engine concept [4], an innovative architecture that aims to replace electric,
hydraulic and pneumatic systems with one single, globally-optimised, electrical system, enabling the proper integration of propulsion and secondary power into the airframe.

In the light of these trends, it becomes less intuitive for an engine sub-system manufacturer to understand which component/technology might offer the highest value contribution in 10, 20 or 50 years. Considering, for instance, the development of an innovative engine intermediate case technology (IMC - Figure 1), engineers and designers must be aware, early on, of the impact of their design choices in a lifecycle perspective.

![Figure 1: a) IMC (dark grey) position in the engine and b) IMC in a front view.](image)

In the aerospace industry today, preliminary design decisions are strongly driven by requirements fulfilment. 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 [25], complemented by cost/benefit analysis and feasibility/manufacturability studies. Targeting lifecycle commitments, these “traditional” dimensions need to be further complemented by criteria able to assess the “goodness” [26] of a design alternative from a system (i.e., assessing the impact on the overall engine/aircraft system) and lifecycle point of view (i.e., assessing the impact on the way the product is operated, maintained, serviced, dismissed, upgraded or recycled).

Moving from these needs, and using as a reference the IMC, the authors have developed a conceptual scenario aiming to support the design teams in making more value-conscious decisions in preliminary design. Figure 2 shows the set of activities, the actors and the related documentation that characterize the scenario, mapping it on the Stage-Gate® process adapted from Cooper [6].

![Figure 2: Scenario phases mapped into the Stage-Gate® [6] process model.](image)

5.1 Phase 1: Defining value drivers and scales

The first activity in the scenario concerns the development and negotiation of the value drivers and scales, which includes the definition of a baseline (minimum acceptance level) and a target (ideal situation) for benchmarking the design concepts from a value perspective.
The project leader, together with the members of the management team, kick-off the development activity by detailing the project context and its metric, on the basis both of the requirements list received from the engine manufacturer and of the specific company’s strategy and objectives. Once the high-level objectives are set, they are cascaded down to component-specific value drivers with the help of a value analyst. The value analyst is a key player in the scenario. While managers and designers are often too deep inside their own working field to have a complete understanding of the implications of a given technical solution, the value analyst possesses wide knowledge and a deep understanding of the dynamics of the product within the overall system and along its lifecycle.

Value drivers are defined from six generic lifecycle-oriented value dimensions, intended as generic value parameters applicable to products of different kinds. These criteria have been identified and developed together with the industrial partners to capture the main value aspects to be addressed by aerospace projects. They are: Performance attributes, Risk, Profitability, Operational Performances, Reliability and Intangibles [27].

The project leader and the managers, supported by the value analyst, specify each driver into criteria, which are more product-specific and directly related to the component under development. Given a value dimension such as Profitability, the team might define machine commonality as a relevant driver, which might be further cascaded down to criteria such as: % of reuse of existing turning machines. Similarly, the value contribution in terms of Operational Performances of two IMC concepts, such as Concept A and Concept B, might be evaluated, using availability as a driver and Mean Time Between Maintenance, Mean Time Between Failure, etc., as criteria. Radar plots can be used to visualize and compare, using a scale from 1 to 9 and (baseline=3, target =7), the value contribution of different IMC concepts (Figure 3).

Some aspects of the product lifecycle may be more important then others, so the team has to assign weights to each dimension, driver and criterion, as well as a baseline and a target for each parameter, growing from the previous experience with the product in question. Weights, baselines, targets and the final value scales are reviewed by the stakeholders and accepted by the management, which sets the expectations for the next gate meeting. After the work is initiated, the Project leader communicates expectations (scales definitions and acceptance criteria) to the project team. If necessary, the project leader assigns resources, such as, additional expertise or additional manpower, to meet the acceptance criteria as closely as possible.

5.2 Phase 2: Gathering value/maturity knowledge from the later lifecycle steps

Once the value drivers, their weights and the acceptance criteria are set, the value analysts prepares the ground for the value assessment task, by establishing links with stakeholders and sources that might possess value-relevant knowledge to compute the value contribution of the sub-system. The value assessment activity cannot be based merely on the geometrical, cost and sales information available within the company, but requires an additional set of models, owned by the customers, to be properly executed. In the IMC example, the value analyst needs to evaluate the IMC integration with the engine, assessing the impact of an IMC concept according to attributes such as payload, range, fuel burn, weight, reliability, maintenance cost, manufacturing cost. Furthermore, he needs to evaluate the impact of a solution at aircraft level, such as on the fuselage, wings, avionics, landing gears, etc. From an operational perspective, it is essential to provide a sound estimation of the expected airline
profitability, gathering knowledge about fleet size, turnaround time, overhauls, etc., and assess how a design alternative can contribute to leverage these parameters. Eventually, when possible, the value analyst might assess the impact of an IMC alternative in terms of intangibles, i.e., in terms of how a component can, mostly indirectly, impact on the passenger satisfaction, feeling and emotions. Such models, when available, are typically dispersed within the extended enterprise. There are, therefore, severe challenges in identifying and sharing them in a satisfactory manner. Privacy, security, and interoperability issues are main inhibitors for an effective sharing, thus value assessment requires an enhanced degree of openness, trust and cooperation throughout the supply chain to facilitate the free exchange of information.

A feasible approach in this context is to treat the models as black boxes, i.e., sharing the location of a particular model and retrieving only the results of a particular calculation, without seeing how the model is configured. The concept of black boxes implies that an object is viewed only in terms of its inputs, outputs and transfer characteristics without any knowledge of its internal workings, that is, its implementation is “opaque”. In this context, the concept of web services can offer a feasible solution by allowing the client (a company that is part of the virtual enterprise) to access a value model. If value models do not exist, the value analyst needs to contact experts in the extended enterprise and, together with them, develop an ad-hoc model. In case the development of quantitative models is too labour-intensive (or based on immature knowledge), the value analyst might gather a multidisciplinary panel of experts that will be in charge of providing a qualitative feedback on the value contribution of a given design alternative.

5.3 Phase 3 & 4: Computing the value models and updating current designs

During the Stage the value analyst, together with the project leader and the designers, initiates the evaluation of the value contribution of the available design concepts. The information about the IMC alternatives developed up to this point is fed into the value models obtained in the previous step, to highlight negatively impacted areas and to establish the necessary corrective actions and to produce a ranking of the current designs.

During the empirical study many stakeholders have expressed a preference towards a single numerical metric for value, both to make easier the comparison between dimensions very different in nature and to mitigate the problem of deriving reliable absolute figures for all the criteria in a preliminary stage. In a nutshell, once a value study is performed for a given component, the outcome of the analysis is expressed in terms of a “delta” between the baseline (i.e., minimum requirement) and the target (i.e., expected outcome). In the spirit of stressing the value contribution of radical designs, the baseline for a new product/service is set on closely related development projects characterized by incremental improvements, while the target is defined on the basis of the customer needs and expectations as well as emerging from system-level long-term forecasts. The output of the value study is eventually expressed using scalars from 1 to 9, which represents the degree to which the design satisfies these two benchmarks. Scalars also work as common denominators that allow the analyst to compare the results of studies targeting heterogeneous value dimensions. All the information regarding the value contribution of such work-in-progress concepts is then fed back to the designers to suggest improvements or areas perceived as weak.

How to facilitate engineers and designers in linking the “value” dimension to the product components, so to enable more value-oriented decisions (and to reduce information overload), has been subject of discussion with the industrial partners. The “theory of cue summation” [28] has been seen as particularly interesting to enhance information processing and to address the problem of information overload. Colours have emerged as one of the key cues for value representation because of the several beneficial effects for decision-making that have been reported by Karayanidis [29] and McNab [30]. The processing of colour has been found to precede the processing of other attributes [29] and, at the same time, to be highly associative [30], creating a constant link between value information and the product model.

Colour-coded 3D CAD models have been proposed as a way to communicate value-related information to the designers. A preliminary mock-up has been realized with the intent to provide a discussion base for value and visualization. The LIVERy (LighTeWt ValUe visualizatoR) [31] conceptual mock-up is intended as a plug-in for a 3D CAD software that exhibits the value contribution of a component as an additional layer of the product structure. The value contribution is displayed across each value dimension and driver using a scale of colours, typically from green (i.e.,
high value contribution) to red (i.e., low value contribution). A conceptual representation of the LIVERY interface is shown in Figure 4.

![Figure 4: Conceptual mock-up of the LIVERY tool (based on Concept A).](image)

Supported by this information, the engineers can review their design, and any necessary changes are considered. If some value dimensions are below the acceptance criteria, the designers can discuss with the project leader the necessary corrective actions, such as modifying a geometry, introducing a new material or involving of external resources to support the development work.

5.4 Phase 5: Documenting value contribution for the Gate meeting

In the Integrated Analysis step, the team compiles all the material needed at the gate. The deliverables are prepared by the team members and forwarded to the project leader. The final value models are computed and included in a Value report, which provides feedback to the decision makers about the level of maturity/fidelity of the models used for the value computation.

The value analyst, assisted by the project leader, computes the state of readiness of the knowledge used to build, populate and compute the value models, using a narrative scale from 1 to 9 over three dimensions: input, method (tool), and expertise (experience) [9]. A rank as 5 indicates an Excellent knowledge maturity, meaning both that: 1) the content and rationale have been tested and proven, reflecting a known confidence; 2) the procedure to produce the content and rationale reflects an approach where tried out methods are used; 3) the workers continually reflect and improve and where lessons learned are recorded. Level 4 is defined as Good and level 3 as Acceptable. Knowledge maturity is Acceptable when: 1) the content and rationale are standardized; 2) there is a greater extent of detailing and definition; 3) the procedure to produce the content and rationale is stable (compared to previous levels) with an element of standardization and repeatability. Level 2 is ranked Dubious and level 1 as Inferior. A knowledge maturity level ranked 1 means that the content and rationale is characterized by instability (e.g., poor/no understanding of knowledge base) and the procedure to produce the content and rationale is dependant on individuals and formalized methods are non-existent (i.e., ad-hoc). The deliverables are finally sent to the management team, who will read the documentation and act as decision makers at the gate meeting. In conclusion, the material is ready and the gate meeting can be held.
5.5 Phase 6: Evaluating value trade-offs at the gate

At the gate meeting, the decision material is reviewed, a questions and answers session with the project leader is performed and a decision is made about the continuation of the project. The discussion between managers, project leader and value analyst aims to resolve the trade-offs between the alternative concepts, mainly focusing on value areas that are perceived as weak (i.e., being below the acceptance level - orange or red). Attention is also given to the areas that substantially differ in perception between the project leader’s statement and the managers’ understanding of what they have reviewed. This session focuses both on the numbers (i.e., value) and on the level of maturity/reliability of the knowledge behind the numbers (i.e., the knowledge maturity). Where needed, additional value analyses are requested to verify the correctness of the value statement and to decide among the trade-offs. Eventually, the gate is opened and expectations for the next gate are communicated to the project leader. To complete the phase the acceptance criteria for the next gate are decided and resources are allocated to the project leader.

6 CONCLUSIONS AND FUTURE WORK

It is a common practice for aerospace sub-system manufacturers to evaluate the “goodness” of a product/service mainly from a “requirements fulfilment” point of view, not taking the bigger picture in consideration. A main limitation of the current practices is that radical designs that would be preferred adopting a system view, tend to be rejected when merely evaluating their technical performances.

The aim of the paper has been to propose a conceptual scenario describing how design alternatives can be developed and assessed with a focus on their value contribution at system level. The scenario aims to improve decision-making in an early development phase, triggering decisions able to add value to customers and stakeholders along the entire product lifecycle. The work has shown that it is crucial to provide continuous feedback to the designers about how a given material/geometry/feature impact the way the product is operated/served/maintained/dismissed in order to drive value-oriented choices. In this spirit, an approach to visualize such contribution directly in a 3D CAD model (across a set of value criteria, dimensions and drivers) has been proposed and it is currently under development.

The scenario and the methodological/technological enablers proposed in the paper can be generalized in other product development contexts, especially in the ones dealing with complex products and featuring Stage-Gate® processes - such as in the naval and automotive industry. The development of an innovative brake-by-wire solution exemplifies well how the proposed approach can be adopted outside the aeronautical domain. Brake-by-wire represents the replacement of traditional brake components such as the pumps, hoses, fluids, belts and vacuum servos and master cylinders with electronic sensors and actuators. At sub-system level, this decision is not merely determined by the degree to which the solution address the list of requirements communicating by the car manufacturer, but needs to take in account a wider set of criteria encompassing how the different customer levels perceive the product from a value perspective. The steps in the scenario can guide the designers in evaluating the trade-offs at the gate, i.e., in defining, weighting and comparing drivers and criteria related to the different value dimensions of the product. The visualization approach can be used to communicate the system level impact of the solution, raising the designers’ awareness on the worsening features (such as weight, part counts, etc.) as well as on the improving features (energy savings, reduced maintenance, etc.) of the solution compared with more traditional options.

Several issues still remain open to make the scenario successful in real life product development projects. Firstly, value assessment requires the sharing of a number of models, heterogeneous and dispersed across the extended enterprise, which requires enhanced enterprise collaboration capabilities to address security and trust issues. Moreover, together with the problem of defining relevant baselines and targets for the value drivers, value assessment suffers from the lack of quantitative data for the value calculation that makes difficult to evaluate trade-offs at the gate, Although the knowledge maturity approach discussed in the paper aims to cope with this issue, further work is needed to make the scenario more transparent and robust.

Despite a preliminary validation has been received through the interaction with several major industrial partners, especially for what concerns value visualization and knowledge maturity, the research is still in its infancy and needs to be followed by a piloting activity in a live product development context. The current efforts are oriented towards the development and refinement of the colour-coding visualization approach, together with the detailed definition of a black-box approach for sharing the value models.
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