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Product-Service Systems across Life Cycle

Virtual Modeling for Lifecycle Performance Assessment in aerospace design

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Abstract

The aim of the paper is to present an approach for the multidisciplinary evaluation of alternative modular concepts in preliminary design with the intent of enhancing engineers' capability to simulate alternative scenarios with different design configurations, so to derive decisions about the most valuable design concepts to further develop. The research contribution is novel in the way that it expands the Set-Based-Engineering approach by addressing the "servitization" challenge in two ways: firstly by the use of value models and sustainability models as decision making support, making possible a preliminary assessment of the value contribution and of the sustainability performances of a design concept; secondly, by the use of functional modelling modules and configurable systems elements for platform-based design, to manage the complex relationships within and between parts of the platform throughout the lifecycle. The paper presents the main features of the approach and introduces an industrial case concerning the development of a module component for an aircraft engine in which the approach is applied for demonstration. The paper finally elaborates on the benefits and implications of the approach in the design process.

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Keywords: model-based design; simulation; platform-based design; value.

1. Introduction

The use of computer-based simulations in product development is nowadays an established practice. The heavily increased computational potential allows manufacturers to model and simulate future products using increasingly sophisticated models of both products and processes. Simulation models cover a large spectrum of design challenges and scenarios: models are used to simulate mechanical properties, manufacturing processes and production flows and as a basis for assessing the impact of a concept in terms of quality, time and cost. All such simulation techniques if applied in parallel allow to analyze a broad range of design alternatives which are systematically narrowed down by eliminating undesirable solutions [1]. This approach to the development of a product is referred in literature as Set-Based Concurrent Engineering [2].

At the same time business models such as revenue sharing agreements, product service systems (PSS) offers [3] and warranty programs, also driven by the pressing environmental challenges, are slowly but constantly changing the way companies approach product development [4][5]. "Servitization" [6] and sustainability challenges are asking engineers to design products fulfilling environmental and lifecycle related needs, causing a perspective shift in engineers' technical horizon. Computer-based simulations however focus more on the estimation of product performances and manufacturing capabilities, rather than in simulating the lifecycle impact of a combined product – service offer [7]. The reason for this is the difficulty to quantify, and thus simulate, service-related information that owns uncertainty and immaturity, especially in the early phases of design [8].

This limitation renders a situation in which early design decisions are supported by simulation models that deliver very

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limited information about product lifecycle and service performances. In a set based concurrent engineering context, such lifecycle and service related information should therefore be integrated to strive for efficiency and effectiveness in the early design stages. This is today particularly relevant in complex development contexts, such as in the case of aerospace product development, where the efficient design and integration of highly technological components on a system is a must of any development project [5]. Here sub-systems and component manufacturers need to operate at a high level of complexity, trading off the engineering performances with cost, time, waste and the lifecycle value generated in service and operation.

The paper proposes an approach for set-based concurrent engineering addressing the “servitization” challenge. The approach is based on the multidisciplinary evaluation of alternative modular design concepts with the intent of enhancing engineers’ capability to simulate alternative scenarios with different design configurations. The “servitization” challenge is addressed in two ways: first by the use of value models as decision making support, enabling a preliminary assessment of the value contribution of a design concept; second, by the use of functional modeling modules and configurable systems elements for platform-based design, to manage the complex relationships within and between parts of the platform throughout the lifecycle.

The paper presents the main features and the logic of the approach and introduces an industrial case concerning the development of a module component for an aircraft engine where the approach is applied for demonstration. The paper finally elaborates on the benefits and implications of the approach in the design process.

2. Research Approach

Participatory action research (PAR)[9] is the approach at the basis of the work presented in this paper. PAR was selected for a number of reasons. Firstly PAR involves the direct participation of both researchers and practitioners in the research design and development, and the involvement of industrial practitioners played a key role for the identification of the industrial problem to be addressed, or, in other words, for the identification of what “needed to be changed” [9]. Secondly because the research effort had both the scientific goal of building knowledge and of solving more practical industrial-related problems with important theoretical implications [9][10]. Thirdly, because PAR allows the development of the knowledge of participants so that they can act as agents of major changes in their organization [11]. Given the focus of the research, i.e. of developing an approach for demonstration, this last point was perceived as a necessary quality of the research approach to promote the final real-world application of the results.

Both data collection and problem definition have been run in collaboration between two academic institutions and one sub-system manufacturer operating in the aerospace business. Data analysis has been run in the light of the current literature on set-based concurrent engineering and on value analysis method for early design. The validity, the rationale and the logic of the approach have been verified and refined through a number of workshops and interviews run in collaboration with the industrial partner. In such occasions a wide number of individuals took part to the PAR initiative. Among those the closest collaborations were established with: a senior company specialist in product development, an expert and developer of knowledge-based systems, industrial experts in platform development and industrial experts in engine systems integration. The applicability of the approach is under verification in a real life demonstrator based on a new concept at the partner company. In the next step of the research the demonstrator will also serve as a reference to validate the effectiveness of the approach and its effect on the design process.

3. The industrial challenge: the “servitization” of value in aerospace development

To be able to run a sustainable business, industrial organizations need to assess their value proposition, which business parts are vulnerable, and what is at the core of the offer that generates value to the customer [12]. Such analysis shall influence all the decisions of a company starting from the way new products and services are designed and developed. Literature highlights that when working in the early design stages, engineers find themselves in the situation of making decisions that will radically impact the value of a future product from a variety of perspectives [36]. The identification of how valuable is a design concept is not straightforward since a wide set of variables and parameters play a relevant role [13]. Different methods in literature support the identification of value in the presence of complex design contexts, among those, Value Engineering [14], TradeSpace exploration [15], and Value Driven Design (VDD) [16], aim to introduce a more value-oriented approach to the design of complex systems.

Research shows that in aerospace component design, preliminary design decisions are strongly driven by requirements fulfilment [5]. Criteria such as high/low cycle fatigue, limit/ultimate load capability, hail ingestion, strength and stiffness, corrosion, oxidation and creep are examples of the evaluation variables of a specific concepts. Shifting toward a servitization perspective, the mere fulfilment of requirements creates a limitation in the fact that potentially valuable solutions tend to be neglected because the focus on technical, requirement-derived, performances, does not allow the designers to understand the value of a solution in a lifecycle and service perspective at system level [17]. Research in system engineering [18] has provided different indications about how the value of a new product shall be determined. Among those contributions authors have identified an important value driver in the capability of maintaining or improving the system functions in the presence of changes [19], and in evaluating system robustness under changing process conditions [15]. In addition, Steiner and Harmon [20] have proposed an extended model of value, adding a new layer of “intangibles” associated with knowledge, emotion and experience. However, the integration of such findings in model-based decision support systems has not yet reached a sufficient level of maturity to become a design practice.

4. The research challenge: The "servitization" of set-based concurrent engineering

In line with the Lean Product Development philosophy [21], Set-based Concurrent Engineering (SBCE) is an approach that is applied to facilitate the design work. The key logic of SBCE is to find a solution as an intersection of a number of feasible parts, rather than find it through iterating point-based solutions [2]. In SBCE designers develop sets of solutions in parallel and with relative independence, and use later additional information to reduce the sets of possible solutions [2]. The PSS scenario opens the spectrum adding solution spaces more difficult to map, embedding the operational and lifecycle performances of a product.

The research challenge given by servitization is to be able to develop a SBCE approach to be used in preliminary design capable of handling the additional complexity given by three sub-challenges. First, the servitization perspective in early design raises the necessity to consider the capability to reduce the design space in pre-embodiment design, while traditionally the SBCE methods are better suited for post-embodiment design, as suggested by for example by Inoue et al. [22]. Second, in early design SBCE cannot deal with well-defined fact and requirements, thus it needs to manage a level of uncertainty about data and information used in the decision-making. Third, the need of providing flexible PSS offering is reflected by the need of delivering flexible designs. Those can be enabled by the development of product platforms to be used as a basis for the integration of variants of solutions in the system. The adaptability of SBCE to platform design is however poorly addressed in literature and only few examples of such kind of implementation are presented [23] [24] [25].

5. An approach to integrate lifecycle value and performance in a multidisciplinary simulation platform

The approach presented in this paper has its roots in previous research on methods and tools for preliminary design decision-making. The approach consists in a combination of methods into a unique approach for modeling lifecycle value and performances in a multidisciplinary simulation platform. The methods used come from two fields: value modeling and platform based engineering. The two areas and the respective methods are briefly summarized in the following two sections.

5.1. Value models to enhance decision makers' awareness in conceptual design

In the conceptual design of a new product development the overall configuration of the future product is defined. Conceptual design is a dynamic stage "*which should be undertaken in the context of an external world*", which means that any aspects related to the product lifecycle, its operational environment and the users of the future product are considered [26]. Different methods and tools to support decision-making in conceptual design are proposed in literature and used in industries. Methods and tolls such as Quality Functional Deployment [27], Pugh Matrixes [28], and different interpretation of Value Models [16][29], are frequently described as capable of supporting engineers in making the right design decisions. Researchers have warned about the hidden trap of using models such as Quality Functional Deployment and its derivative, that are based on assumptions which validity is often questionable, and on qualitative assessment which relies on experience and intuition [30][31]. Nevertheless such methods are widely adopted and can be consider as one of the most common design practice thanks to their usability and easiness of communication.

In conceptual design the use of value models is increasingly discussed in order to enhance engineers' awareness. Value models can be used both as boundary objects [32], around which the value discussion develops [33], and as tools for the preliminary assessment of the "goodness" of a design [16]. The value model adopted in the approach proposed in this paper is based on the approach named "Early Value Oriented Design Exploration with Knowledge Maturity" (EVOKE)[13] which run a trade off analysis between different design concepts based on their capability of satisfying contrasting stakeholders needs in relation to a baseline and a target. The EVOKE approach is based on three matrixes (Weighting matrix, Input matrix, CODA matrix) and a Value Creation Strategy (VCS). Figure 1 show a summarized picture of the EVOKE approach structure.

The approach is grounded on the definition of a VCS, a document collecting prioritized needs and expectations from stakeholders at different levels of the supply chain. The role of the VCS is to iteratively collect the needs and expectations of all the stakeholders that will play a role in the lifecycle of the future product, thus involving direct and indirect customers in the supply chain, but also institutions and authorities responsible, for instance, of defining market or environmental regulations. The VCS embeds the lifecycle needs and expectation of the future product and provides both a prioritized set of needs to the weighting matrix and preliminary indications to the designers for concept definition. The weighting matrix correlates the customer needs with internally defined value drivers, expressing design directions that are identified as relevant by the design team itself, so to provide a list of weighted value drivers for the final calculation. The input matrix collects the design information about the early definition of the concepts (i.e. data about engineering parameters of the designs, form physical characteristics to produceability and availability of knowledge). Such information is inputted to the CODA matrix [30], where the design team assess the value of a concept using non linear merit functions to correlate the value drivers defined in the weighting matrix and the engineering characteristic defined in the input matrix. At the end of such process the Design Merit of a design concept is outputted as a percentage of the satisfaction of the overall set of needs.

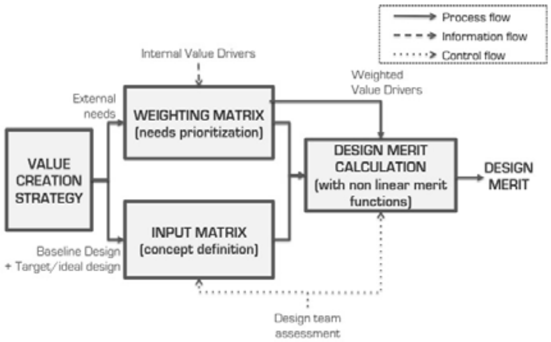

Fig. 1. Schematic representation of the logic of the EVOKE approach presented in [11].

5.2. Configurable systems elements for platform-based design

Traditionally, platform-based design has focused on providing high commonality of parts to gain the benefit of scale in production. However, to support the development phase, particularly concept phases, part-based platforms are inadequate [34]. The platform approach used in this paper is based on model called the Configurable Component concept, first developed by Claesson [35].

The model represents systems and their sub-systems as objects related to each other. Each system is represented by a Configurable Component (CC), which in turn can inhabit several design solutions (DSs), functional requirements (FRs) and constraints (C) (Figure 2). To fulfil a range of requirements, the configurable component can chose between different design solutions, each of which is scalable using a set of parameters. Thus, the model incorporates scalable bandwidth as well as modular bandwidth. The core of the CC is the design rationale. It relates functional requirements (FRs) to the design solutions (DSs).

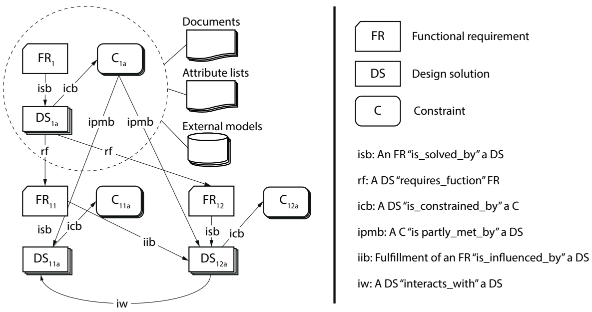

Fig. 2. The F-M tree constitutes the building blocks of a configurable component (adapted from Claesson [35]).

Based on the CC-concept, Levandowski et al. [23] suggest using function-means (F-M) modelling to structure the design in pre-embodiment phases. It gives support to design synthesis as well as analysing the goodness of the design using e.g. axiomatic design. After narrowing down, infeasible designs in the pre-embodiment phase, the functional models can be connected to detailed CAD and physics models for further analysis

6. Case Study: A conjunct approach for value modeling and platform-based design.

The use of a conjunct approach embedding both value modeling and platform based designed is demonstrated though the use of a case study, meant to verify the applicability of the approach in a real-life case. The case consists on the design of a turbine rear module structure (Figure 3) for a geared fan commercial aircraft engine expected to enter into service in 10-15 years. The new engine concept owns particular features and functionalities that provide the basic specifications, in terms of geometry and performances, to create the "virtual engine" upon which the different design concepts of the turbine real module can be traded-off. An industrialization scenario is also set to plan the development stages, the entry into production, and the delivery rate of the engine for the next 30 years.

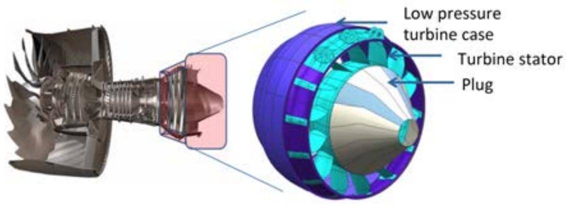

Fig. 3. Positioning and main components of a turbine real module structure.

For the sake of the demonstrator two main value creation strategy has been defined: the first focusing on the delivery of a "high performance" turbine module concept, the second focusing instead on a "low cost" concept. The two VCS have rendered a different list of stakeholders' needs and expectations with consequent different prioritizations of the value drivers used in the evaluation model. For instance, in the first VCS the value drivers linked to the mission performances (e.g. specific thrust, specific fuel consumption, drag) are highly relevant, while, in the second VCS, drivers linked to cost of realization, development efficiency and design robustness are prioritized.

6.1. Logic of the approach

The design concepts are traded-off by calculating the design value using the EVOKE approach with the integration of functional modelling modules and configurable systems elements. Figure 4 summarizes the logic of the approach dividing horizontally the steps of the approach derived by EVOKE and the steps enabled by the use of a Configurable Component environment. Figure 4 also highlights, with different styles of the arrows, the process flow, the information flow and the control flow. The approach starts with the definition of one or more VCS, which express different lifecycle needs and expectations of the customers, rendering a list of rank-weighted value drivers. Based on the VCS the design team defines the list of functional requirements in the CC environment. Those will be used as input for the definition of the configurable systems elements. Such step renders a list of different Design Solutions (DS) that will be later assessed in the Design Merit Calculation matrix derived from the EVOKE approach. Such process of defining DS from configurable systems elements substitutes the "input matrix" used in the original EVOKE approach (see Figure 4), thus the engineering characteristics of the concepts are no longer singularly and subjectively inputted in the model. Concurrently the Weighting Matrix used in the EVOKE process plays the role of prioritizing the value drivers (VD) from the VCS by correlating them with needs and expectations internal to the company.

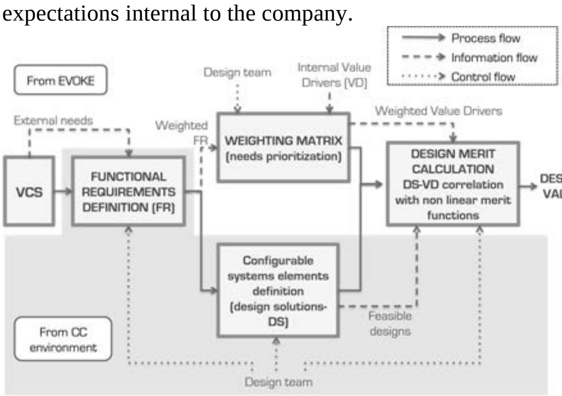

Fig. 4. The conjunct approach for virtual modeling of lifecycle performances embedding Value-Modeling and the Configurable Component approach for platform based design.

The design merit calculation matrix correlates the weighted VD outputted from the weighting matrix and the DS outputted from the CC environment. This is with the use of non-linear merit functions [25]. The approach generates a value score for each feasible design (identified as a DS) based on the degree of satisfaction of the value drivers, eventually enabling the decision makers to trade-off functionalities or simulate different scenarios by modifying VD prioritization.

7. Discussion and conclusions

Companies working as suppliers of complex products or systems face often the challenge of developing new products by taking into consideration the effect that a single design variation have on the overall system performance. The use of a platform-based design approach is often the solution applied by many companies to face this challenge. The capability to develop concepts that are modular in respect to pre-existing architectures can generate consistent competitive advantages. The applicability and the functionalities of existing platform are often already verified, thus an incremental innovation based on a shared underlying platform reduces the development risks in terms of unexpected consequences and late design changes.

However, even in the presence of an underlying platform, what is often not clear to engineers is to understand which design variation is the most valuable among a set of design alternatives. This is true not only concerning different levels of platform compliance, but also in terms of final product performances, and of satisfaction of stakeholders' needs at a system level. While the technical performances, in terms for instance, of strengths, resistance or weight, can be simulated virtually in CAD environment, the aspects related to the platform compliance and to the value generation in respect of stakeholders' needs are often assessed through qualitative models. This design process practice causes problems in preliminary design. Here the design space is open, and the number of possible design variations is very high, thus it becomes overly complex to manage the heterogeneous amount of information needed to have a complete understanding of the potential value of a design alternative. The capability of integrating the evaluation of value-related aspects (e.g. platform compliance and stakeholders' need satisfaction) in a virtual simulation would render a situation in which many design variations of a concept would be verified in an automatic fashion from a multidisciplinary perspective.

The work presented in this paper contributes to a cross-disciplinary research area between systems engineering and set-based concurrent engineering, and focus particularly on the development of model-driven decision support systems for platform-based design incorporating a service perspective. The approach proposed targets one aspect of the overall research challenge, i.e. the modeling of design concepts in respect to configurable systems elements to evaluate the value of different concepts. The work is a first attempt to verify through a demonstrator in a real case scenario the benefit of the conjunct use of methods developed for platform development in set-based concurrent engineering, and methods development for the value assessment of product-service combinations.

The approach contributes to the design practice in the way that it supports engineers in making more aware trade-off decisions upon different design alternatives with lifecycle consideration, uncovering performances linked to the service dimension. The use of value models and functional modeling modules has been demonstrated in a variety of industrial contexts in a separated fashion. This work targets the demonstration of the two approaches in a unique virtual model in an aerospace product development context. The approach is at the basis of a demonstrator that will be deployed in the context of aerospace component development for the simulation of alternative design configurations of a turbine rear module structure for an aircraft engine. Through the use of value modeling techniques the approach aims at incorporating the consideration of an increasingly higher number of service aspects when trading off different concepts in decision-making. Such need emerges in response to the servitization process that is impacting, among others, the aerospace industry and is declined in new types of lifecycle-oriented business offerings for aircraft engines.

What differentiate the use of the proposed approach in the aerospace context with the use in other industrial environment is the content that populates the models, rather than the structure and logic, which is independent from the context of application. For such reason the authors argue that the approach shall be seen as generalizable in other design environment featuring a similar level of complexity.

In line with what introduced in the case study description, the future research will focus on the demonstration of the approach or a full-scale design problem to evaluate the effects on the design process.

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