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VIRTUAL CONTEXTUAL VALIDATION OF TECHNOLOGIES AND METHODS FOR PRODUCT DEVELOPMENT

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1. Introduction

Despite significant validation and even qualification efforts, complex industrial product development projects frequently struggle with difficulties in integrating new technologies. A recent example, the introduction of new battery technologies in the Boeing 787 aircraft caused un-desired problems for the manufacturer and drove new practices [Williard et al. 2013]. The effort and cost of validating and verifying new technologies in aerospace typically require building and introducing the technology into advanced physical products, where time and cost are high even before product development starts. Therefore, advanced validation programs usually focus on one concept in detail, rather than exploring many different options. The sub sequent business driven product development will then apply the technology in products that deviate from the context wherein they have been validated. Similar arguments apply also for new development methods, which need to be validated prior to the implementation and use in order to avoid risk and extra work.

To address this, the concept of a virtual demonstrator aims to provide a product context in which both novel methods and novel technologies can be first validated. The novel technologies need to be evaluated and compared based on how they perform in an applied system context. Novel methods on the other hand, need to be explained and understood by the users and brought up to a maturity level fit for industrial implementation. Academic research has over the years proposed a plethora of design methods and tools developed with the intent of improving the efficiency and effectiveness of the product development process and there is a well recognized challenge to successfully bridge the step from research into practice. As highlighted by Wallace [2011] and reiterated by Gericke and Eckert [2015] the bi-lateral transfer of knowledge between academia and practitioners poses a key question to the research community about how research can be made more actionable. Still, there is a huge gap between the methods available and the actual state of the art in current product development processes. A new method or tool has to reach a certain readiness level to be applied. About this topic, Birkhofer et al. [2004] have discussed the knowledge transfer problem by defining the “ten commandments” of knowledge transfer, stressing the need of methods and tools that address real company needs and integrate with designers work practices. Stetter and Lindemann [2005] have further proposed a framework for knowledge transfer based on initiation, analysis, choice and adaptation, implementation and evaluation of the method. A similar work by Geis et al. [2008] have proposed four “pillars” respectively promoting the simplification, the adaptation, the promotion and the development and implementation of appropriate training for the design methods, so to successfully implement a new method in the daily job routine.

This even increases the differences between theory and practice in product development methodology, since it doesn't allow for new methods to evolve to a higher readiness level. As a consequence, few have seen a maturity level to be deployed in real cases. To bridge this gap, a transfer of knowledge has to be achieved by providing an environment that allows technologies to mature in their readiness level.

This paper reports from an ongoing research effort in aerospace aiming to develop such “virtual demonstrator” for methods, tools and technologies, using virtual definitions of a product context for a turbine rear module of a commercial aircraft engine. The virtual demonstrator enables new concepts to be integrated in a system and validates them contextually. The implementation of alternative design solutions or methodologies are tested and validated without the cost associated with a real world demonstrator. In an initial stage, three concepts are being validated in the virtual demonstrator, two methods – Value Driven Design, and Functional modelling – and one technology – Ceramic Matrix Composites (CMC).

Following an introduction to the technology and methods, these are applied in an industrial example. The virtual demonstrator serves to validate the interplay between methods and technologies and is explained through a high temperature component development in a commercial aircraft engine.

2. Validation in a virtual demonstrator

A virtual demonstrator can represent a digital environment with a certain degree of realism and industrial relevance. Advances in computer modelling and visualization have matured immensely over the last decade, at least partially as a successful result of research and development aiming to reduce the need of physical testing. The Virtual Demonstrator naturally includes geometrical representations, yet can equally represent functional, logical and other forms of virtual representation. A common theme is the role of providing means to bring novel techniques into a context as a part of maturing the understanding and representation of a forthcoming solution. The sections below review and introduce selected key concepts of maturing technology, value modelling and functional modelling subsequently how these are used in the validation steps of a virtual demonstrator.

One mechanism to represent and assess a technology is in measuring how mature it is from a system perspective. The notation of Technology Readiness Levels "TRL" [Mankins 1996] has become common practice in many industries, via its original use in space and aerospace. It brings technologies from the state (TRL 1) via development of functionality (TRL 3) to the demonstration and validation phases and the industrialization and use phase where technologies used are ultimately standardized. TRL6 is commonly used as the required level of readiness in aerospace industry before industrial product development and realization can be launched. Introducing technologies with a lower level of technology implies a too high risk for the developing company. In the process of maturing a technology from TRL 3 to TRL 6 the importance of a relevant context becomes increasingly important. To be validated on TRL 6 a "System/subsystem model or prototype demonstration in a relevant environment (ground or space)" has to be performed, which in aerospace requires physical demonstration of the technology in an almost real product environment. Above TRL 6, the demonstrated technology can be introduced to a real industrial development and realization context.

In Figure 1 the virtual demonstrator is positioned as a means to bridge the steps from functional demonstrators (TRL 3) via laboratory demonstrators (TRL 4) up to a first validation of relevant environment (TRL 5). Precisely what is considered to be "relevant" environment is to be judged by the respective technology and its context. For new methods, (left in figure), gaps in current practices are readably identified in advance of novel development, whereas the successful introduction into established practice often follow after years of efforts.

It is argued that a virtual demonstrator can support how a technology matures into a product context by allowing new technologies to be first validated in a product context. The same virtual demonstrator is proposed to support the validation of new methods and capabilities in advance of implementation.

In the following sections, two new development methods are introduced, serving as examples of design methods that benefit from validation in a context. The technology to be validated in the virtual demonstrator will be introduced together with the industrial example.

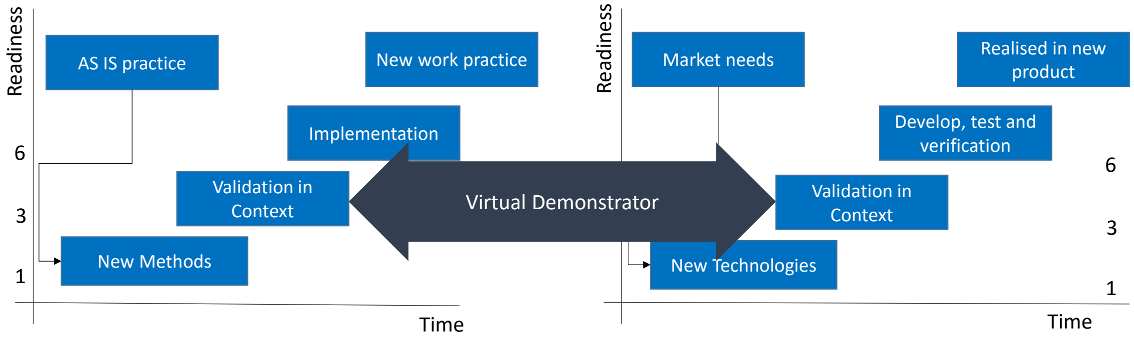

Figure 1. Virtual demonstrator to validate context of methods and technologies

Value modelling

Any design activity is driven by the desire of creating the product that will ultimately generate the highest value for the customers and the stakeholders by satisfying different needs and expectations. Many authors have agreed that the value of a product has to be found at the intersection of tangible and intangible dimensions [Brandstötter et al. 2003], [Tukker and Tischner 2006], [Wang et al. 2011], [Cavalieri and Pezzotta 2012]. In the context of early decision making in a complex design environment there is a need to "objectify" value, making it quantifiable [Bertoni et al. 2013]. Research on Systems Engineering [INCOSE 2006] and on Value Driven Design [Collopy and Hollingsworth 2011] has highlighted the importance of linking value to the product/system functions. The value of a design concept can be "objectified" by assessing the concept's capability to improve the main functions and/or delivering additional functions, while reducing unwanted functions and support functions [Lindstedt and Burenius 2003].

McManus et al. [2007] highlighted that a system designer has typically only influence over the "form" of a system. This "form" is mediated by the operational environment that determines if the system meets the needs and expectations, and therefore delivers value to the stakeholders. Based on such an idea a list of criteria, named "ilities", has been defined expressing the value of a concept specifying the degree to which a system is able to maintain, or even improve, its functions in the presence of change.

Lindstedt and Burenius [2003] also stressed the relevance of functions for value evaluation. They have proposed a definition of value as the ratio between the "total functionalities" provided by a product and the "total expenditures" that the customer faces buying and owning the product all along its life.

In summary, the assessment of value and the trade-off of design concepts can be exploited by enabling the identification and analysis of how well a solution satisfies needs and expectations in relation to the functions that are delivered in the system. Value modeling is largely justified in theory, shows a good potential, and is in a phase where it needs to be introduced into a realistic context to gain better feedback from non-specialists and prepare implementation.

The research presented in this paper approaches the value modelling of different design alternatives by characterising the different functionalities provided by the product in relation to the satisfaction of stakeholders' need and expectations. Different design solutions will grant different combinations of delivered functionalities, thus different fulfilment of needs and expectations. The cost of realisation of a specific design solutions, or of combination of them, is not computed as a part of the value modelling, rather it is "embedded" as a specific characteristic of the different design options, enabling an eventual trade-off of the value/cost ratio for different design combination. Value modelling will be further introduced as the Virtual Demonstration process is presented.

Functional modelling

Another method area is the use of formal models and modelling methods in engineering design and has provided the basis for improved decision making for the past half century [Duffy and Andreasen 1995]. The prevailing paradigm in many engineering companies is a design support structure constituted of tightly connected CAD and CAE systems. While this provides excellent capabilities for analysis and synthesis based on geometric representations of the design, it fails to support phases where ideas and concepts are explored without physical embodiment [Gedell 2011]. In these early phases of ideation and technology consideration, formal support is rare in practice.

Functional models, if used right, support concept development with their inherent capability to express structures without explicit physical attachment. Those structures are made up of elements expressing what the product is supposed to do, Functional Requirements (FRs), and principal abstract solutions that fulfill those functions, Design Solutions (DSs), [Schachinger and Johannesson 2000]. Some functional models, such as the Enhanced Function-Means (EF-M) Model, provide means for modeling the design spaces necessary for exploring several concepts in parallel. By assigning several alternative design solutions for one functional requirement, several conceptual solutions are modeled simultaneously [Schachinger and Johannesson 2000]. If applied to various levels in the EF-M tree, morphological combinations of the design solutions form a large number of discrete design concepts, or architectural options [Levandowski et al. 2014].

Several benefits are associated to modeling and developing parallel functional concepts. First, the modelling of concepts at this stage requires minimal effort, yet provides a basis for discussion and decision making. Design decisions in the concept stage are known to create ripple effects on cost, quality and lead-time in later stages. Formal modelling and analysis of the models provide real data to base the decisions on [Raudberget et al. 2015]. Second, functional modelling of concepts enables comparison of a large array of concepts building on different technologies. Third, functional models enable a novel take on design and knowledge reuse. They provide a baseline that may be expanded with new functionality. By already mentioned morphology, several new architectural options may be generated based on just a few new branches in the function-means tree [Raudberget et al. 2015].

As for value modeling methods, functional modeling need to be introduced into richer user context to be validated, explained and improved.

Virtual demonstration validation steps

The contextual validation is organised into four steps, those are outlined in Figure 2 and described below. The validation process combines functional modeling and value modeling to allow assessment of new technologies in a product context.

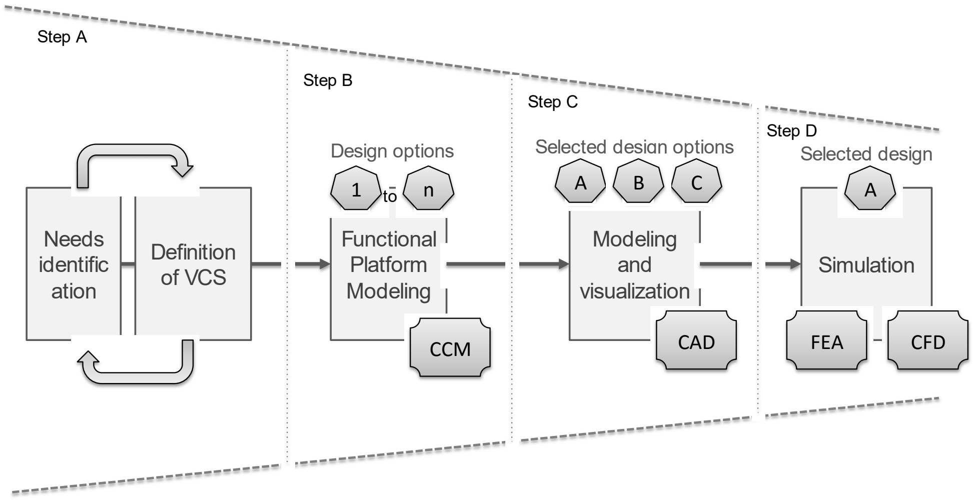

Figure 2. Steps for the validation of the Virtual Demonstrator

a. Identification and issuing of a Value Creation Strategy

Value modeling seek to improve how stakeholders needs and expectations can drive development. Such representation need to have two main characteristics:

- They need to be relevant for the development engineers.

- They need to express and communicate the original design intent to the supply chain partners.

The demonstrator uses, as a reference point, the concept of Value Creation Strategy (VCS), first proposed by Monceaux and Kossmann [2012] to enhance traditional requirements management within an extended enterprise. The VCS is the prioritized set of needs that capture the intent of the overall design task and is designed to facilitate understanding also to different design teams and suppliers.

Creating a common VCS allow all partners to work towards a shared objective even before requirements are fixed, thus reducing time and resources spent in preliminary activities not driven by clear customer indications.

Essentially, the concept of VCS can be considered as a common platform, or framework, to make more explicit how valuable a new design solution is in relation to a set of rank-weighted and prioritized needs. By introducing the new value modeling technique into this phase, it can be validated in a natural way.

b. Functional platform modeling of alternative design concepts

The engineering design team takes the VCS, plus any known explicit requirements and knowledge about existing design solutions to identify alternative design options. Typically, the design team is represented by several parties of different competence, and the work is a combination of creative and analytical tasks. In this phase, a modelling tool designed to enable functional modelling, can represent alternative conceptual solutions for an attractive technology that then is targeted for validation.

As a tool to facilitate the functional modelling the CCM (Configurable Components Modeller) is employed. It allows the engineers to describe the required functions of the product, together with solutions of for these. In addition it allows for modelling the constraints enforced upon those solutions. The different requirements and solutions are then combined into Configurable Components and their interactions modelled.

c. Modeling and visualisation of most promising alternative options

In a third step, the engineering team needs to limit the number of design options to define sufficient detail of each concept and enable further analysis of the selected options. Typically, this steps include geometrical modeling which is limited to a sub-set of all possible combinations identified in step “b”.

The use of graphical visualization, especially linked to CAD environment, has been acknowledged by industrial experts to provide a better overview of the problem when compared to numerical tables, to better contextualize the systems information and to make it easier to discover patterns and find outliers in the analysis. An effective visual representation of information is a key support for design. It makes easier for humans to build and use their mental models when searching for solutions [Simon 1996] and it fosters communication by achieving situation awareness so to derive knowledge for actions [Klein 1989], [Endsley 1995].

d. Evaluation through simulation

Depending on the nature of the design study, and which stakeholder needs and requirements need to be evaluated, fundamentally different simulation techniques need to be used. Where physical behaviour needs to be understood, such as mechanical integrity of a part, engineers normally use computational methods like Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD). In cases where non-geometrical effects need to be simulated, such as the maturity level of suppliers or impact on production lead time other techniques are used. This is not further explored in this paper but explained for completeness.

3. Industrial example - a turbine outlet assembly

The example deals with high temperature structural components - in this case a rear turbine structure (TRS) and an exhaust cone - in a jet engine. The overall design challenge is to meet airline expectations on improved performance. For the components, this means reducing weight while allowing even higher temperatures. Cost competition still prevails, thus the design solutions should also be characterised with low cost. Further, the aerospace business has rigorous certification procedures, why the maturation of plausible technologies is a necessary means. This drives technology development into advanced demonstration and validation initiatives in advance of industrial realisation.

An illustrative example is the introduction of high performance materials like the Ceramic Matrix Composite (CMC) that have become increasingly interesting in aerospace applications [Boyer et al. 2015]. Highly specialized knowledge and equipment have been accumulated over the years in Swedish academia and institutes in the form of fragmented research efforts. The need for synthesizing the knowledge and experience is apparent. A virtual demonstrator i) creates a more comprehensive understanding of the design task; ii) the possibility to validate technology in relevant context, iii) explore the design space and iv) to identify knowledge and a technology gap, and finally v) the possibility to involve potential suppliers in early stages. A more comprehensive understanding of the design task creates opportunities to identify key competences and technologies for the specific application and more targeted research efforts can be initiated. The dispersed competence and technology makes it more difficult and emphasizes the need to start this process in the early stages. The possibility to introduce technology, although virtually, in industrial context and more realistic conditions create opportunities to validate technologies and thereby the prerequisites to raising the maturity and TRL-level. In the case of the CMC-material no shelf solution is available. However, the demonstrator makes it possible to virtually explore the design space and define a material specification which needs to be fulfilled by future solutions. This includes multiple load cases and joining solutions which are unique for the application. A fully developed and certified CMC-solution will be very costly. Consequently, it is of great importance to evaluate the value for customers and stakeholders and the functionality prior to realisation. The potential of an integrated value and functional modelling is thereby especially apparent with high performance technology which involves major challenges and risks in development. Also the benefits are evident if weak links and technology gap can be identified in early stages. Finally, in the case of the CMC-material there is lack of suppliers of CMC-materials. However, the virtual demonstrator opens up the possibility to involve potential suppliers in early stages. The demonstrator facilitates the communication of a potential OEM's needs, general technical challenges, business opportunities and risks. Thereby the prerequisites to involve and identify a potential supplier are enhanced.

By introducing the CMC technologies in candidate design concepts, the associated modelling and simulation activities can be used as the first steps for future hardware demonstrators. The advantage of the virtual example is the ability to represent a much wider design space, where more alternative arrangements, sizes and conditions can be explored. As the concepts are being refined and ultimately physically build, the design variability vanishes.

a. Identification and issuing of a Value Creation Strategy

In the example, the Value Creation Strategy emphasises different stakeholder's needs in combination, such as low cost and high performance. Other stakeholder needs such as the maturity of technology, produce ability and maintainability are examples of other stakeholder needs that - although also important - can be judged less critical in comparison to low cost and high performance. For the simplistic purpose of the example, the Value Creation Strategy emphasise the combination of low cost and high performance. Consequently the design team is set out to search for such solutions that are strong in these values. As a reference, the currently used solutions are typically advanced superalloys that are relatively heavy and increasingly costly (since ever more advanced alloys are considered for each new generation of engines).

b. Functional platform modeling of alternative architectural options

The functional modelling approach to the design challenge begins with identifying the core functional requirements (FR) from the stakeholders' values. Design solutions (DS), either singular or including alternatives, were chosen to match the FRs. In this example case, several new functions also sprouted from workshops of a multi-disciplinary team of engineers. Those were first captured in traditional form as text and sketches, and then converted into the FR-DS schematic. In these workshops, about 15 individual configurations were created.

Based on the functional structure, a total of 41 conceptual design solutions could be identified, whereof 27 options were considered feasible. The FM structure was then clustered into configurable components [Claesson 2006]. This component structure was used as the basic layout for the assembly structure in the following geometrical product models. Furthermore, the interactions modelled in the FMT can provide valuable insight for further analysis in the pre-embodiment stage, such as through DSM (Design Structure Matrices).

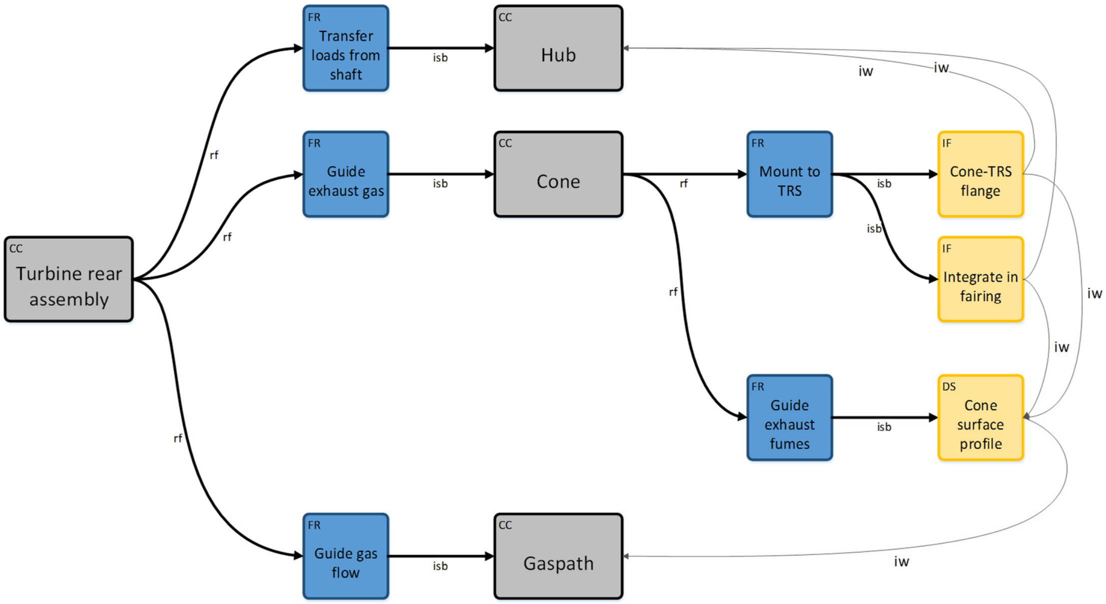

Figure 3. A section of the functions-means tree of the turbine rear assembly, focusing on the CC "cone"

In Figure 3, functional requirements (FR) are displayed in blue and design solutions (DS) in orange, configurable components (CC) in grey.
In Figure 4, a small part of the FM structure of the turbine rear assembly is shown. It focuses on the CC "Cone" and shows the interacts with (iw) connections to other CC. The entire structure consists of more elements, but it simplified here for illustratory purposes. For example, the other CCs are collapsed, their internal FM structure being hidden. Therefore, the iw connections to the DS of the neighbouring CC are collected towards the parent CC. The iw connections are the basis for an export to DSM and further analyses.

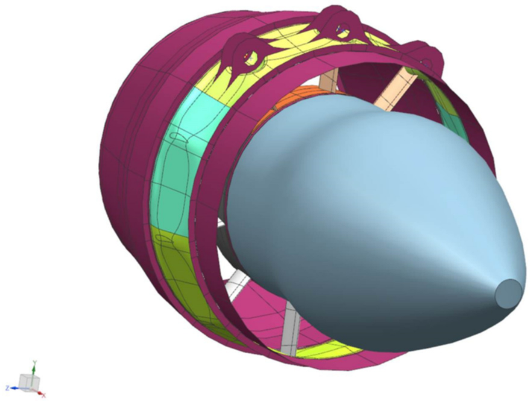

Figure 4. Geometric representation of the turbine rear assembly, with Cone in steel blue

c. Modeling and visualisation of most promising alternative options

In the specific example, the key design solutions candidates for CMC technologies applied on exit cones are modeled in a CAD environment. In the current example, a technology program had just completed a feasibility study of a CMC exit cone that is represented as one design solution to satisfy the functional requirements. A 3D geometric lay out of a rear turbine assembly is presented in Figure 3.

d. Evaluation through simulation

Following the Value Creation Strategy, that stated weight and performance to be of highest priority, the available design solutions were analysed and the CMC cone concepts came out as well performing. The weight of the possible solutions, quantifiable via the geometric model, indicates substantial potential for weight reduction in comparation to currentlyexisting designs. The performance of CMC parts in terms of thermal integrity is attractive, and are of at least equally high potential compared to current solutions. In addition, the cost of material can be kept low.

The current simulation setup is missing the assessment of production and assembly as well as the integration in the overall airplane. Judged merely on the premises stressed in the Value Creation Strategy, the concept is highly ranked.

4. Results and discussion

The result presented is a virtual demonstrator concept, consisting of a four step virtual validation process to validate new methods and technologies in a product context. The approach combines novel value modeling methods together with functional modeling methods. It has been applied onto an industrial case where new technologies in the form of Ceramic Metal Composites is being considered for introduction in high temperature jet engine components. Overall the virtual demonstrator approach has allowed contributions from different academic disciplines to be combined with a richer industrial case.

As a first result, the functional modelling method allowed all possible design alternatives generated in a conventional concept generation workshop to be represented in one single platform model. Based on applying a functional modeling tool and method, the search for architectural options was supported even further. More alternatives could be identified than from the initial design team workshop.

Secondly, assessing the value of the concepts generated by new technology insertion, using value drivers that are specifically produced for the company reflects real value for the company. The introduction of Value Creation Strategy guided the design team to search for more novel approaches that were driven primarily by low weight and high performance. The same Value Creation Strategy was used also to evaluate the concepts.

A third, essential, result is linking current design processes of the company to the new notions of value and functional concept modelling. This can be used to justify further design studies to be launched, knowing that the concepts that are chosen have the desired value profile.

Deliberately "neglecting" the potential limitations of known technologies allowed novel solutions to be identified. Notably, CMC's are known to face challenges in aspects such as repariability and maintainability [Boyer et al. 2015].

The results at present are not complete as this paper reports from an ongoing research project, yet there are several promising results visible already. In terms of Setter and Lindemann's [2005] process, the results in this paper reflects choice and adaptation, implementation and evaluation of the design methodology. Though the integration with current best practice at the company is shown, a future step is to make the methods an integral part of the design process.

5. Conclusions and further work

The Virtual Demonstrator is still in formation and is being defined to allow simultaneous contextual validation of new methods and new technologies. Value modeling methods are introduced together with functional modeling methods into a virtual validation process. This allow wider search of value adding concepts and comparison of new technologies at the same time.

The introduction of value driven design technologies introduces the search and evaluation of important aspects. The platform model further allows integration of technology design solutions generated in other projects. Further work in the project will focus on completing the design study outlined in chapter 3. The integration between the functional model and the generation of the necessary product models needed to complete simulations is ongoing. From the value modelling perspective, value modelling can be coupled to the functional model as functionality is the basis for value from a user perspective. Visualisation and exploration of a design spectrum before delimiting the solution down to a feasable set for geometrical interpretation is merely one.

The engineering design literature offers a plethora of new methods, tools and technologies to improve the effectiveness and the efficiency of the product development process. When it comes to the real application of such new methods, these are often applied in idealistic case studies, characterised by well defined needs and features. Literature highlights the presence of a knowledge gap between the new method developed and their application in real cases, mostly due to the low generalizability of the approaches given the low level of maturity achieve in the development. In a parallel with technology development, also new method and tools can be compared to a “readiness level” that need to be raised over a certain level of maturity in order to enable their industrial application. Such need to be advanced enough to overcome the risk adversity and the endemic resistance to change of an industrial environment.

The research presented in this paper deals with the challenge of bringing new methods and tools to a higher “readiness level” by a virtual contextual validation. The paper has presented a research effort within an aerospace product development context to virtually validate the applicability of new a set of new design methods in a preliminary design phase. A four step approach for the validation of a virtual demonstrator has been presented and contextualised in a turbine outlet assembly. The approach features the integration of a methods for value assessment of design alternatives using Value Driven Design methods and functional platform modelling techniques developed in the frame of set-based concurrent engineering. In addition, a fully developed and certified CMC-solution will be very costly. Consequently, it is of great importance to evaluate the value for customers and stakeholders and the functionality prior to realization. The potential of an integrated value and functional modeling is thereby especially apparent with high performance technology which involves major challenges and risks in development.

The work presented in the case study represents one of the first attempts of integration of the methods developed in the two research area is a unique demonstration environment. Further research is currently undergoing to refine the virtual validation context. The relevance and importance of contextual validation for methods and technologies is promising, yet not fully tested.

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