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MEDIATING CONSTRAINTS ACROSS DESIGN AND MANUFACTURING USING PLATFORM-BASED MANUFACTURING OPERATIONS

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Abstract

To meet the needs of an array of customers, platforms can provide means to achieve commonality and distinctiveness among a family of products. However, typically the producibility of product variants are not ensured until the late platform development phases. This may lead to increased development lead-time, due to lack of integration across design and manufacturing. To be better suited in making early producibility assessments, a model to improve the integration across product platforms and manufacturing platforms is presented. The model is embodying manufacturing operations and marries platform models of two technical systems – products and manufacturing equipment. To serve the concurrency needed to explore cross product-manufacturing alternatives during the early phases of platform development, manufacturing operations can be modeled to serve improved integration of product platforms and manufacturing platforms. By modeling functions, control parameters, and key characteristics, the constraints across design and manufacturing can be mediated.

Keywords: Product families, Concurrent Engineering (CE), Integrated product development, Platform concept development, Manufacturing operations

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1 INTRODUCTION

Product platforms can be employed to serve a wide variety of customers, i.e. mass customization, and at the same time to decrease the number of unique components among a family of distinctive products (Jiao *et al.* 2007). By these means, manufacturing companies can benefit from economies of scale in production, and increase sales and gross profit margins aggregated over the product lifecycle (Meyer *et al.* 2017). However, despite these benefits there is a lack of support that promotes reuse of assets beyond physical components. Especially during the early phases of platform development when no embodiment exists. To gain a first-mover advantage on a changing market, manufacturing companies therefore need better tools and methods that serves mass customization during the development phases (Ferguson *et al.* 2013).

While the need to respond to customer needs faster is prevalent, this may not be sufficient to be competitive on the marketplace. Still, manufacturing companies struggle to achieve high productivity and mitigate the occurrences of production disturbances (Bokrantz *et al.* 2016). Beyond meeting the needs of end-customers, products also need to be adapted to fit the needs of other stakeholders, such as taking the dynamic capabilities in manufacturing in to account during the early development stages. Koufteros *et al.* (2014) studied the link between product platforms, concurrent engineering, and manufacturing practices. They demonstrated that firm performance is mediated by the manufacturing processes. They reason that the effects are indirect, i.e. the product development strategies affect manufacturing practices which then will impact the firm performance. Upon reflection, for manufacturing companies to seize a competitive advantage and reduce lead-time, the interplay between products and manufacturing systems may be decisive for firm performance.

1.1 Design, Manufacturing and Platform-Based Development

There are several process-focused approaches to integrate design and manufacturing, e.g. integrated product development (Andreasen and Hein 1987), or concurrent engineering (Prasad 1996). There are also several methods to ensure producibility of products, such as Design for Manufacturing (DfM) and Design for Assembly (DfA). DfM focuses on the part design, while DfA focuses on simplification of the assembly structure (Boothroyd 1994). Vallhagen *et al.* (2013) suggest that producibility aspects should link the function and performance of the product.

While DfM and DfA have been implemented to ensure producibility of single products, ensuring producibility of a family of products has received little attention (Simpson 2003). However, some work has recognized the potential to integrate product platforms and manufacturing platforms, e.g. Jiao *et al.* (2006) and Michaelis (2013). There are also some examples of how to integrate DfMA techniques in platform-based design (Emmatty and Sarmah 2012) and to assess producibility of a product family (Jonas Landahl *et al.* 2016).

During the early phases of platform development, product concepts and manufacturing concepts may be explored in parallel. However, the concurrent processes needed to support this parallel exploration rely heavily on the existing models that connects the product-manufacturing domains. Current platform approaches focus on modeling of products and manufacturing systems separately, which is why parallel exploration of the two becomes difficult. While there are models that represent products and manufacturing systems respectively, there is a dearth of elaborated models that represent the integration of the two.

To model the integration of product platforms and manufacturing platforms, the interplay between products and manufacturing systems needs to be better understood (Bokrantz *et al.* 2017). In this paper, an initial attempt to embody this interplay is made to subsequently support the exploration of product and manufacturing alternatives during the early phases of platform development.

2 RESEARCH APPROACH

This paper aims to support parallel design-manufacturing exploration during platform concept development. The goal is to provide a model that can be used to identify and mediate constraints across product platforms and manufacturing platforms. The approach is illustrated using a case from the aerospace industry. The case is prepared as a part of a long running collaboration with GKN Aerospace Engine System Sweden. The purpose of using a real-life case is to substantiate the research findings in an industrial context and provide consistency to the findings. By interviewing system specialists, examining design and manufacturing guidelines, as well as observing operational manufacturing processes at the shop floor, in-depth knowledge of products, manufacturing equipment, tools and processes have been extracted. To propel the research work, a research question was formulated: *how can the interplay between product and manufacturing solutions be modeled to identify and mediate across design and manufacturing constraints during platform concept development?*

3 FRAME OF REFERENCE

To better understand how product platforms and manufacturing platforms can be better integrated, this section presents a body of theory on models that represents platform entities, transformation processes and manufacturing operations.

3.1 Platform Theory

Product platforms are commonly used to combine and configure an array of physical parts into a family of distinctive products (Meyer and Lehnerd 1997). These physical parts, or modules, are created with a static set of customer requirements in mind. This view on platforms is sub-optimal for businesses where customers constantly demand new functionality, or where changes to the product are commonplace due to introduction of new requirements. Current platform practice lack efficient methods and representations that serves the development advances in-between the evolving requirements and the finalized designs. These advances are crucial for design engineers to understand and articulate the designs existence and to be able to make further improvements of them. To increase support during the development phases, some research proposes reuse of entities beyond physical components. For example, Alblas and Wortmann (2009) suggest reuse using function platforms. Function platforms enable reuse of functions as well as the configuration of a function family, rather than a part family. On the same note, Levandowski *et al.* (2014b), among others, propose using function modeling to describe platforms during the early stages of development to increase reusability.

3.1.1 Platform System Objects based on Function Modeling

Product platforms based on physical parts has at least two shortcomings, 1) economies of scale are not provided during the development phases and 2) the platform entities are represented as static parts. To better serve a changing market and the dynamic capabilities of manufacturing, there is a need to represent adaptable platform entities. Claesson (2006) proposed an approach to model abstract platform entities, *configurable components* (CCs), in contrast to physical parts. This approach is based on systems theory principles (Hitchins 2003) and design theory (Hubka and Eder 1988, Andreasen 1991). A CC object can be modeled as an entire system family, with information about the system solution itself, the means of composing system variants, as well as its underlying requirements and motivations, i.e. its *design rationale* (DR).

There are several approaches that aim to capture the *design rationale* (DR). Design rationale includes the justifications for why it exists; alternatives, trade-offs, and argumentation (Lee 1997). One method of including such information is Function-Means (F-M) modeling. F-M modeling is a systematic way of finding *design solutions* (DSs) that fulfill *functional requirements* (FRs) (Andreasen 1980). An FR explains what a product, or an element of a product, actively or passively will do. The FRs motivate the downright existence of a specific solution. The DSs can be tangible, e.g. components or features, or intangible, e.g. services or software. An F-M model has a hierarchical structure, where systems are decomposed into subordinate sub-systems. The F-M tree follows Hubka's law: *"the primary functions of a machine system are supported by a hierarchy of subordinate functions, which are determined by the chosen means"*. Schachinger and Johannesson (2000) enhanced the F-M model by separating functional requirements from non-functional requirements, where the non-functional requirements are represented as constraints (Cs); see Figure 1.

An F-M tree can be modeled to represent a wide range of requirements and solutions in certain levels; the static level, conceptual level, concrete level and the physical level (Levandowski *et al.* 2014b). These four levels of the F-M tree can be elaborated as the requirements and solutions mature during the development process. Thus, the F-M model becomes richer as information becomes available and continually gets modeled.

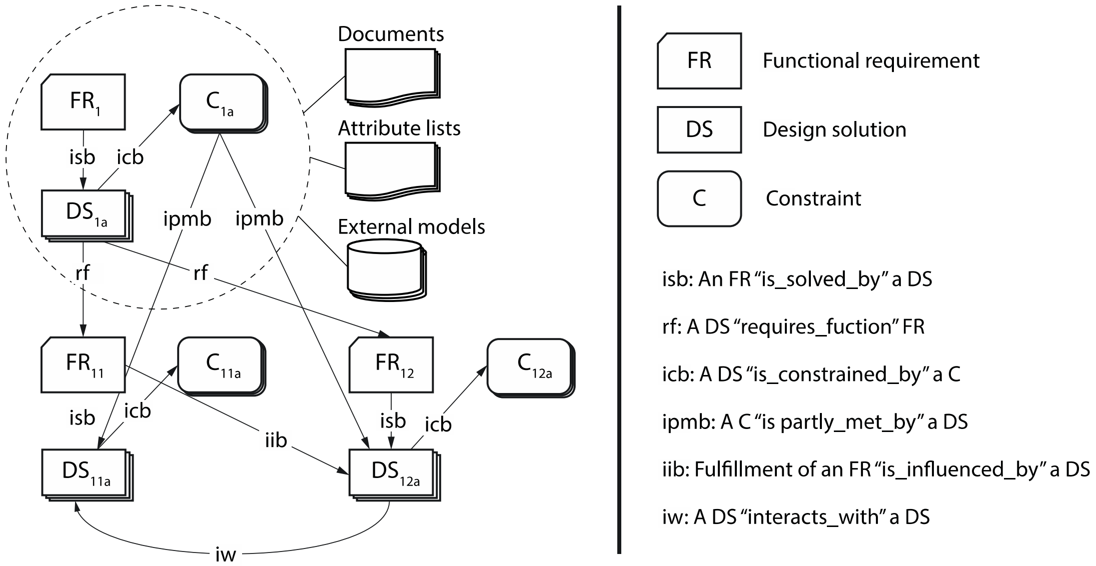

Figure 1. Enhanced function-means tree (as drawn by Levandowski et al. (2014a), adapted from Johannesson and Claesson (2005))

Currently, F-M modeling has been adopted to represent products. However, to realize a tangible product and reach the materialization of the physical level, raw material needs to be transformed during the manufacturing process, or a number of sub-entities, i.e. the manufacturing operations. To embody the interplay between products and manufacturing systems, manufacturing operations and transformations need to be represented, and modeled.

3.2 Modeling Transformation Processes as Manufacturing Operations

Researchers have recognized the potential of using transformation processes to support product modeling. Hubka and Eder (1988) developed the Theory of Technical Systems (TTS) to support engineering design of technical systems. The technical system (TS) supports the transformation process (TrfP) to fulfill certain functions. For example, the technical system of a washing machine has the function of cleaning clothes. The TTS transformation process works as a 'black box', providing an input and an output of the so-called operands (Od1 and Od2). In the example, dirty clothes are the input while clean clothes are the output. A TS delivers the exerted effects (ΣEf) that perform the desired transformation of an operand. A model depicting a transformation system, operands, and a transformation process is illustrated in Figure 2.

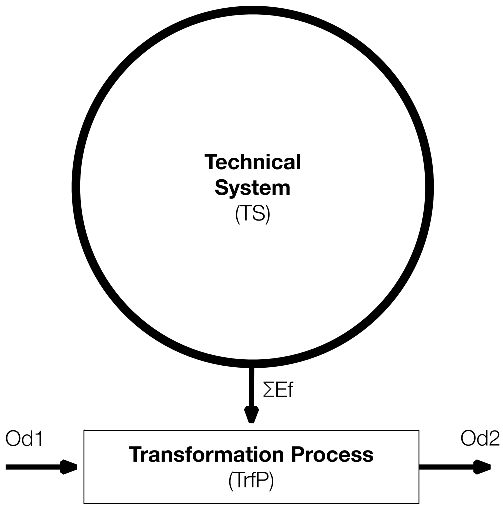

Figure 2. A model of a transformation system, redrawn from Hubka and Eder (1988)

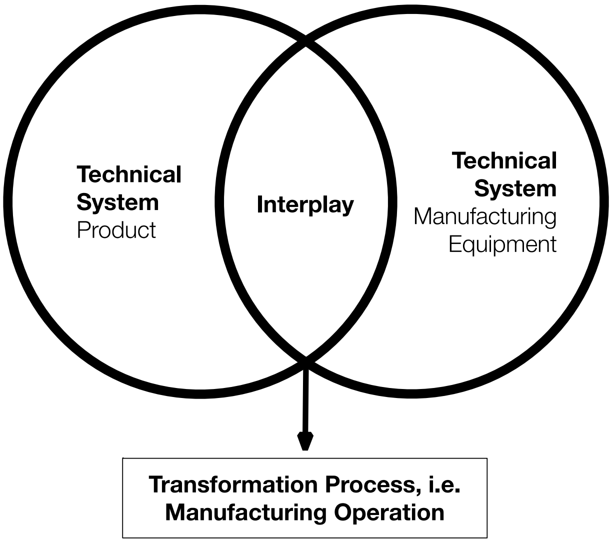

Figure 3. Two technical systems, product and manufacturing equipment, and the interplay between them represented in a manufacturing operation

In the same fashion as transformation processes can support product modeling, they can also support the integration of design and manufacturing. Attri and Grover (2012) applied the TTS approach to describe the manufacturing system as a facility where transformation processes convert inputs into outputs. Hubka and Eder (1988) also provides an example where the TrfP is a manufacturing operation 'wire drawing' and the TS is the wire drawing machine. In this example, one single technical system is modeled to be utilized during the manufacturing operation – the wire drawing machine (the manufacturing equipment). However, in fact a transformation process representing a manufacturing operation includes at least two technical systems – an envisioned product and the manufacturing equipment. Therefore, the model may be improved to better support the interplay of these two technical systems.

A manufacturing operation represents the physical lifecycle meeting where the products meet the manufacturing equipment and vice versa (Bokrantz *et al.* 2017). In this meeting, the two systems will limit, or constrain, each other on how they will perform. During development phases, this interplay may represent the producibility of the envisioned product. Thus, the transformation that occur during a manufacturing operation represent the interplay of the two technical systems. Unlike the TTS model, the interplay of the two technical systems are meeting in a manufacturing operation model. This interplay is illustrated in Figure 3.

4 SUGGESTED APPROACH

In an attempt to find remedy in the research question posed in this paper, constraints that may limit the feasibility of cross product-manufacturing solutions needs to be better understood. In an initial effort, the interplay between design and manufacturing are assumed and represented, i.e. the manufacturing operation. To represent the interplay of the products and the manufacturing equipment, parameters related to both design and manufacturing are considered. This approach is adopted from Madrid *et al.* (2016). These parameters will influence, or control, the outcome of the operation. To categorize these control parameters, an Ishikawa diagram, commonly used to represent sources of variation (Söderberg *et al.* 2006), is adopted. The control parameters are denoted as 'q', adopted from Mørup (1993). Along a sequence of manufacturing operations, a set of key characteristics (KCs), i.e. the product characteristics, are created, transformed, or both, until the product is manufactured to a desired state. The variation of the KCs is critical to the function and performance of the product (Thornton 2004). The parameters (q) will affect the state of the product in-between the operations in two ways: 1) contribute to the variation of the KCs, and 2) constrain the function and performance of the envisioned products, the manufacturing equipment, or both. In this way, the deviation between the output and the input of each operation can describe the variation propagation as well as how the interplay across design and manufacturing will constrain the design space of one another.

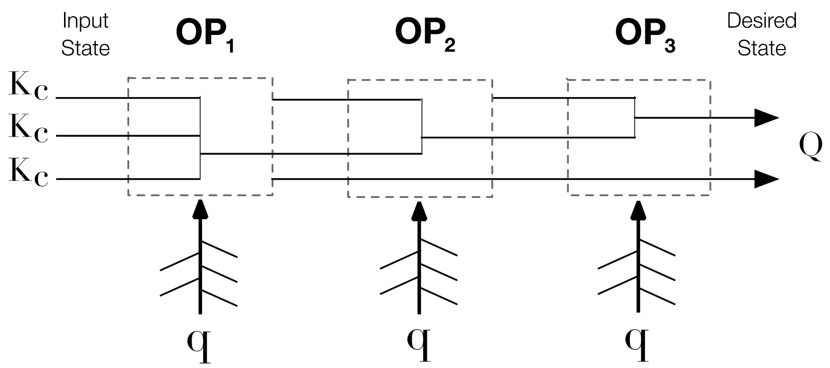

Figure 4. In a sequence of manufacturing operations, KCs propagate while the qs regulate them towards the desired state (Q) (adapted from Madrid et al. (2016))

At the desired stage, the product ought to contain the features, properties, and characteristics that carry the performance and quality of the product in accordance to the customer needs and requirements (Q). The concept of Q-quality was adopted from Mørup (1993). A set of KCs that are influenced by a variety of qs through a sequence of operations towards the desired state (Q) is illustrated in Figure 4.

To support the modeling and integration of product and manufacturing solutions through manufacturing operations during the early phases of platform development a function approach is adopted from Michaelis *et al.* (2015). Essential to the fulfillment of the transformation is the operational functions that define what the operation shall do. The functions of the manufacturing operation are modeled as functional requirements (FRs). During the manufacturing operation, the manufacturing equipment is utilized to produce the envisioned products. Therefore, the model needs to represent FRs that relates to the two technical systems – the product and the manufacturing equipment. By modeling connections crossing the two technical systems ('is solved utilizing'), the product side of the platform (product variant) and the manufacturing side of the platform (manufacturing variant) are married.

To further detail the operation model and encompass a wide variety of both product and manufacturing solutions, the interplay between parameters (qs) adhering to both design and manufacturing are modeled. These qs represent the constraints that influence how the design spaces may constrain one another. Thus, the KCs that are transformed along an input and an output state may be constrained by the qs. While the needs of the transformation are modeled as FRs, the KCs and the qs are modeled to represent the transformation of parameters. The KCs describe the product characteristics critical to the product performance, i.e. the product design solutions to be materialized in the operations. The interplay of qs (q_{design}, $q_{material}$, q_{method}, $q_{equipment}$, $q_{process}$) may therefore influence the interplay of product-manufacturing solutions. The platform-based manufacturing operation model embodies the interplay across design and manufacturing by the inclusion of FRs, qs, and KCs, see Figure 5.

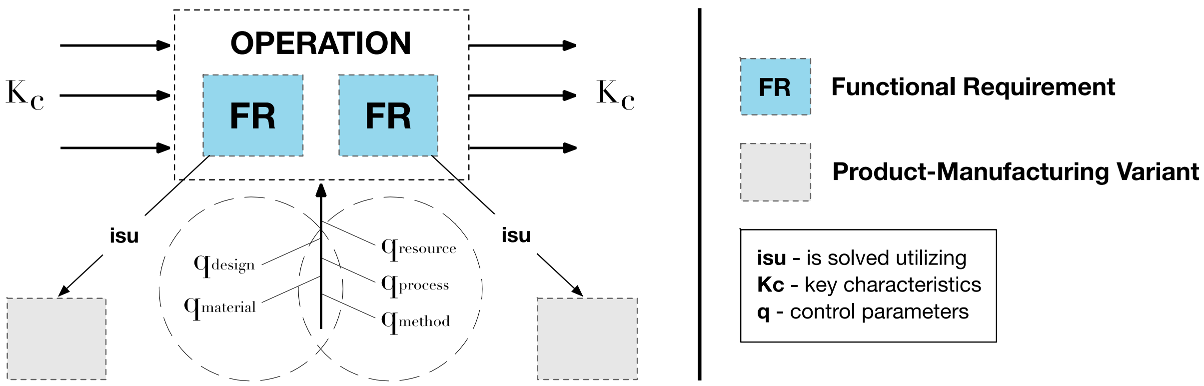

Figure 5. A platform-based manufacturing operation model that takes both design and manufacturing into account

5 ILLUSTRATING CASE

To illustrate the approach, a case from the aerospace industry is presented. The case company, GKN Aerospace Engine Systems Sweden, is an aero engine component manufacturer that designs and manufactures components and sub-systems for commercial jet engines that comes in different sizes to fit different sizes of aircrafts. The studied product, Turbine Rear Structure (TRS), is located at the rear of the engine and is illustrated in Figure 6. Each TRS is manufactured at a yearly volume of a few hundred units and is customized for different customers. The case company has the ambition to reduce the time from a request given by an Original Equipment Manufacturer (OEM) to an offer of feasible conceptual alternatives from three months to three weeks. To be equipped for this, an imminent concern is to include knowledge about manufacturing during the platform concept development.

Product: A new requirement is introduced – the TRS needs to endure higher operating temperatures, from 700°C to 900°C. Because of the new requirement, the thermal loads in the TRS will increase. An FR is modeled ('FR – Convey thermal loads') to explicate the need to reduce the deformation effects of the increased thermal loads. To solve the FR, several design solutions (DSs) can be explored (e.g. 'DS – Cooling system', 'DS – Heat shield', 'DS – Thermal matching', and 'DS – Thermal resistant material'). In this case, 'DS – Thermal matching' is further explored. In simple terms this is made possible by varying the variant parameter (VP) 'lean angle' of the mid-section, shown in Figure 7. To encompass various engine sizes, the VPs 'inner radius' and 'outer radius' are modeled. The next step is to explore how the TRS variants can be manufactured.

Manufacturing Equipment: The TRS can be manufactured in various ways. This case illustrates a welding assembly scenario, which is why the TRS is divided into segments, shown in Figure 7. The TRS as well as the manufacturing resources available (including fixture, robot, and welding equipment and tools) are modeled in the same fashion as the TRS. Four alternative welding technologies are explored – 'TIG', 'Plasma', 'Laser' and 'EB'. In addition, there are producibility constraints to take into consideration related to, among others, 'Robustness', 'Accessibility', and 'Weld quality'. The next step is to model the manufacturing operations, including the FRs, qs, and KCs that are needed to marry the technical systems and identify constraints across design and manufacturing. Two manufacturing operations – *fixturing* and *welding* – are modeled.

Fixturing Operation: Three functions are modeled: i) the parts (denoted A, B, and C in Figure 8) needs to be accommodated, ii) the parts need to be placed into the fixture, and iii) six degrees of freedom needs to be locked. The control parameters, 'locating scheme' (q_{design} and $q_{equipment}$), will affect the assembly variation in the operation. Any deviations will affect the KCs 'gap' and 'flush' between the interfaces of the parts. The locating scheme represents the physical contacts between parts and the fixture (denoted A1, A2, A3, B1, B2, and C1).

Welding Operation: Three functions are modeled: i) the parts (denoted A, B, C, and D) needs to be accommodated, ii) the weld beam needs to be moved along the weld split lines (denoted X and Y), and iii) the parts need to be fused together. The control parameters 'rim height' (q_{design}) as well as 'welding speed' and 'welding power' ($q_{process}$) will affect welding transformation in the operation. Thus, determining the outcome (denoted E), KCs 'weld bead', and the Heat Affected Zone ('HAZ'). The integrated platform model is illustrated in Figure 8.

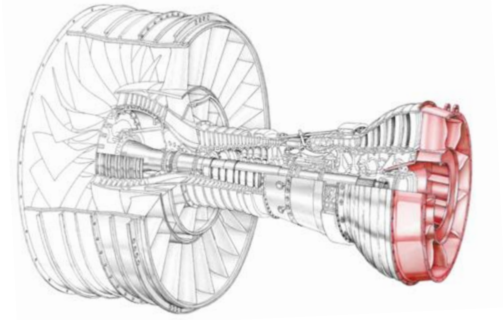

Figure 6. An aero engine with the TRS to the right (Levandowski et al. 2014a)

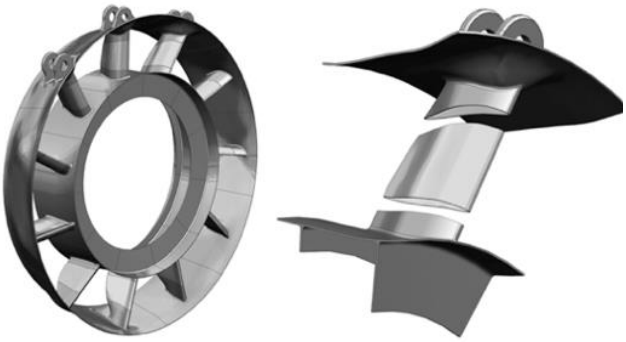

Figure 7. The TRS divided into segments, which are welded together in an assembly process

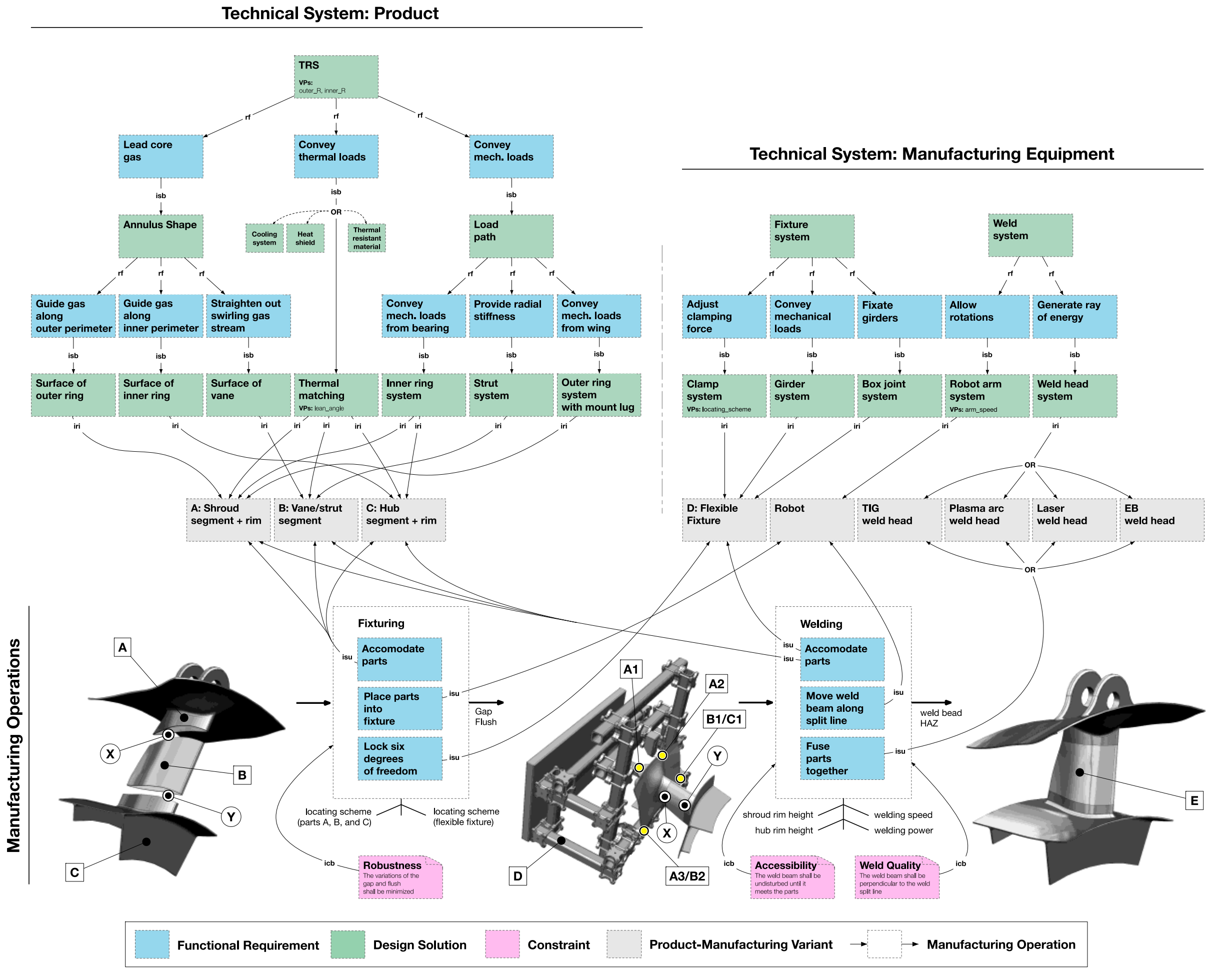

Figure 8. The platform-based manufacturing operation model is used to marry the envisioned product solutions and the manufacturing resources available

When the manufacturing operations are well understood, there is a good possibility to find relationships among the constraints and mediate across them. The relationships between the control parameters and the KCs are important in supporting design exploration in the intersection of design and manufacturing. In fact, these relationships can support in finding producible design alternatives by constraining the design space of the TRS alternatives and the welding alternatives concurrently, e.g. (J. Landahl *et al.* 2016).

Due to pedagogical reasons the interactions (iws) across DSs in the function structure are omitted. Also, the number of manufacturing operations are limited for the same reason. In reality, the welding operation requires that the parts (A, B, and C) are already tack welded. In Figure 8, the notation 'OR' indicates that there are alternative design solutions to explore, while 'iri' stands for 'is realized in' and demonstrates the solutions that are encompassed in either a product variant or a manufacturing resource. Moreover, it is important to note that all the models, VPs, qs and KCs are merely representing a subset of the reality.

6 DISCUSSION

The common approach in dealing with product variety is to treat every variant separately. A great strength with the proposed platform approach is the ability to reuse the function structure for all emerging product variants, including the various alternatives. In fact, the whole tree structure is a valuable source for design engineers to support their understanding of the rationale behind the products, manufacturing operations, and resources. For example, occasionally design engineers need to be informed of those important assets, not least because of people's tendency to forget, or when employees are introduced to the products and the manufacturing systems. The approach is especially supportive in scenarios when a new product variant needs to be developed, or when the capability in manufacturing needs to be improved, e.g. if a machine needs to be upgraded with a new designed tool, or a new machine is purchased. By adding or removing functionality based on specific customer needs, immature solutions can be explored before committing to a product solution, a manufacturing operation, or a certain resource. It could even be applicable in scenarios when two companies share a common platform – one company that develops the product variants and the other developing the equipment and tools utilized to manufacture the emerging product variants. In this way, the design engineers can share their needs more effectively, and the understanding of those needs will underpin each respective design rationale. Yet, in such a scenario there might be conflicts of interest as some of the information may infringe on the intellectual assets of either of the companies. However, such predicaments can be mitigated through e.g. signing agreements that allows sharing of sensitive information in long term collaborations between the companies.

In addition, a software tool that supports the modeling approach is constantly being improved in line with any novel research advancements. Based on this piece of research, it would be interesting to model an even more complex system and evaluate the practical use of the suggested approach.

7 CONCLUSION

In this paper, a model that can be used to identify and mediate constraints across product platforms and manufacturing platforms is presented. The model is embodying a platform-based manufacturing operation that marries two technical systems – products and manufacturing equipment. To serve the concurrency needed to explore cross product-manufacturing alternatives during platform concept development, the integrated platform approach may be a way to support design engineers to mediate constraints across design and manufacturing.

We reason that the interplay of control parameters (qs) adhering to design and manufacturing will influence the key characteristics (KCs) which variation propagates through a set of manufacturing operations. This interplay has a direct effect on how design and manufacturing will constrain the design space of one another.

By modeling the information of functional requirements (FRs), qs, and KCs, both design and manufacturing constraints can be identified. As provided in the case, the q-parameter 'locating scheme' of the H-segment and the fixture respectively will affect the 'gap' and 'flush' of the interfaces between the assembled parts. Also, the q-parameter 'rim height', that may define where the weld split lines can be placed, is dependent on the choice of welding technology (based on e.g. the expected 'HAZ' from the welding operation) and the welding tool accessibility. These identified relations may support the parallel exploration of product and manufacturing alternatives during platform concept development while models are still immature, thus when the cost to modify and improve the designs and operations is rather insignificant. However, the use of the integrated platform model to support such practical cross product-manufacturing exploration is a matter of future work.

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