ON THE INTERPLAY BETWEEN PLATFORM CONCEPT DEVELOPMENT AND PRODUCTION MAINTENANCE

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Abstract

To meet a broad customer-base, platforms can be used to achieve commonality and distinctiveness among a family of products. However, producibility of product variants are typically not ensured until late in the platform development phases. This may lead to increased production disturbances. To understand challenges in ensuring producibility of a product family in the early phases of platform development, this paper adopts the concept of lifecycle meetings to describe the interplay between platform concept development and production maintenance. Based on this description, we reason that to make early and credible cross product-production decisions, production system capabilities ought to be regarded as dynamic rather than static. While static implies as designed, dynamic implies change over time. In this paper, maintenance is regarded as one dynamic aspect of production. This reasoning is supported by a theoretical perspective and an illustrating case from the aerospace industry. The contribution of this paper may form the basis for future research on platform development and the effect of product variety on production systems.

Keywords: Product families, Concurrent Engineering (CE), Integrated product development, Platform concept development, Production maintenance

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1 INTRODUCTION

In the fierce competition among manufacturing companies, production systems need to deliver high productivity while supporting a variety of distinctive products that meets the needs of a wide range of customers. Product platforms have proven efficient in providing this distinctiveness and at the same time support reuse of components among a set of products (Jiao et al., 2007). However, a challenge is to ensure producibility of the set of products. Especially during phases when no embodiment is yet developed and decisions are taken on scarce information. Producibility refers to the relative effort needed to produce a set of products using available production technology. To support producibility assessments, a prevalent industrial need is to better exchange information across design and production during the early platform development phases (Wheelwright and Clark, 1992).

To manage the variety that a set of product variants induce, various types of flexibility in production is needed (Sethi and Sethi, 1990). Flexibility in production implies that the production system can be used to produce a set of distinctive products. To ensure flexibility, production systems need to be designed with certain capabilities to reflect both current and future needs. This paper focuses on capabilities in terms of the function and performance of equipment that is necessary to produce products that meets the needs of a wide range of customers. Yet, the majority of the modern manufacturing industry struggles with low productivity and frequent production disturbances. Industrial practice suggests dealing with production disturbances and improving productivity by ensuring the function and performance of equipment through continuous maintenance activities.

In essence, there is a conflict in the simultaneous search for improved productivity in production and the increasing diversity of products. This conflict is further accentuated by current digitalization trends that envisions both higher levels of automation, resource efficiency, and productivity in production, as well as extended variety of technologies in products. Most research concerning production disturbances focus on the increased integration between production maintenance and the development of production systems. However, the integration between production maintenance and the early phases of platform development has been rather unexplored. To ensure producibility of the emerging product variants during the early platform development phases and achieve high productivity in production, production maintenance aspects must be taken into consideration. However, commonly producibility is ensured during late development phases and the production system capabilities are often regarded as they were designed, i.e. static. In contrast, these capabilities do change over time, i.e. are dynamic. Therefore, considering production system capabilities as dynamic may serve increased credibility of cross product-production decisions during the early phases of platform development. This paper considers maintenance as one such dynamic aspect of production.

1.1 The Interface between Products and Production Systems

Products are developed to fulfil intended functionality derived from customer needs. The anticipated functions to be embodied can be dealt with differently, taking different product lifecycle phases into account – such as concept development, design, production, distribution, maintenance and end of life.

It is rare that design engineers both develop and design products and the equipment needed to produce those products. Commonly, design engineers do not take information of e.g. production disturbances and maintenance requirements into sufficient consideration during the early development phases. However, several authors have proposed benefits of parallel exploration of products and production systems, such as integrated product development (Andreasen and Hein, 1987), co-development paradigms e.g. (Tolio et al., 2010), and set-based concurrent engineering e.g. (Levandowski et al., 2014a). On the same note, Koufteros et al. (2014) empirically demonstrated that both product platforms and concurrent engineering have positive effects on firm performance (delivery, product quality, product innovation). Specifically, they showed that these effects are mediated by manufacturing practices. Since "excellence in product development can easily be eroded by manufacturing weaknesses" (p. 92), this mediation implies that concurrent engineering is necessary. Therefore, it is critical to provide design engineers with the support needed to explore products and production systems in concurrency. This integrated development implies taking both decisions about the product and production in to account so that their synergy can match the ever-changing market.

To accomplish efficient integrated development, design engineers need to be supported in keeping track of the functions of the envisioned production equipment that is used to produce the envisioned product.

One important aspect is to enable efficient information exchange across design and production by integrating IT systems. In design, the information exchange is commonly managed by using Product Lifecycle Management (PLM) systems. In production maintenance, the information exchange is commonly managed by using Computerized Maintenance Management Systems (CMMS). More fundamentally, however, to enable co-development the interplay between platform concept development and production maintenance needs to be understood. Pedersen (2010) applied and improved a framework to explain interfaces between product and production life phases to fit platform development, known as lifecycle meetings. For example, Levandowski et al. (2014a) studied the interplay between product and production platforms using manufacturing operations as connecting elements. The interfaces of product and production life phases may shed light on how e.g. complexity and its associated costs propagate from early platform development phases to late production phases.
However, first there is an important distinction to make between product lifecycles and production system lifecycles. A product lifecycle includes the life phases of a product. In contrast, the production system lifecycle includes the lifecycles of an arsenal of equipment. Yet, each equipment in the production system have their own lifecycle respectively. An example of an interplay between the two lifecycles is the lifecycle meeting between the "production phase" (product lifecycle) and the "use phase" (production system lifecycle). This meeting can be represented by the manufacturing processes, where production equipment is utilized to produce the emerging product variants.

2 RESEARCH SCOPE AND APPROACH

This paper aims at describing the interfaces across the lifecycles of products and production systems to better understand the interplay between platform concept development and production maintenance. Well-understood interfaces may contribute to future research initiatives that focus on the development of methods and IT support makes collaboration across lifecycle activities more efficient. To study these interfaces, a lifecycle perspective was adopted. More specifically, the concept of lifecycle meetings, developed by Pedersen (2010) was used. This meeting is described by providing a theoretical perspective as well as an illustrating example from the aerospace industry. The example is based on a long running collaboration with GKN Aerospace Sweden AB. By interviewing system specialists, discussing with maintenance managers and engineers, and examining relevant documentation, such as design guidelines and process descriptions, in-depth knowledge of products, production equipment, tools and processes have been extracted. The contributions from this paper may form the basis for future research on the integration between product and production to support early producibility assessments of product variants. In particular, production maintenance is highlighted as an important aspect of producibility assessment.

3 FRAME OF REFERENCE

To provide a theoretical basis that underpins the research conducted in this paper, a body of research on platforms, producibility, and maintenance in product and production system lifecycles is presented.

3.1 Platform Theory

Research on platforms typically aim to understand how scale benefits in production can be met by sharing manufactured parts among a family of distinctive products (Jiao et al., 2007). However, the industrial need and the direction of research points at creating rigorous models to support the mass customization development process (Ferguson et al., 2013), and especially during the early phases when no product embodiment is available. A prevailing concern for such a course is the risk of overlooking production aspects. In the pursuit of a producible product family, there is a need to reduce time-consuming and costly physical verification and assess the producibility based on what is already known.

3.1.1 Integrated Product and Production Platforms

The corporate view on product platforms is that a collection of physical parts can be configured into distinctive products (Meyer and Lehnerd, 1997). These physical parts, or modules, are typically created with a static set of customer requirements in mind. However, this view on platforms is sub-optimal for businesses where customers constantly demand new functionality, or where changes to the products are commonplace due to introduction of new requirements (Landahl et al., 2014). In brief, such platforms support a low number of parts in production, but provide little support during the development phases. To increase support during development, there are other ways to maintain efficiency over time. For example, design reuse could encompass other things than physical parts. Alblas and Wortmann (2009) suggest design reuse using function platforms. Function platforms enable reuse of functions as well as the configuration of a function family, rather than a part family. To increase the ability to reuse, Levandowski et al. (2014b) propose function modelling techniques to describe product platforms during the early phases of development.

3.1.2 Producibility of Product Variants

There are several approaches for integrating production knowledge in product design, e.g. Design for Manufacturing (DfM) and Design for Assembly (DfA). These approaches provide design engineers with guidelines on how to design products and assess producibility. Producibility links the functions, characteristics and performance of products together (Vallhagen et al., 2013). Emmatty and Sarmah (2012) provide an example on how to integrate DfM and DfA in platform-based design. Similarly, Michaelis et al. (2015) describes how co-development of products and production systems can be accomplished using an integrated platform approach. While function models can represent designs, production systems may also be modelled in a similar fashion. An example of design and producibility exploration of a set of product variants using set-based concurrent engineering approaches is provided by Landahl et al. (2016).

3.2 Maintenance in Product and Production System Lifecycles

In this paper, we differentiate between maintenance as a product lifecycle phase and a production system lifecycle phase. While some authors, e.g. ElMaraghy et al. (2012), argue that a production system should be regarded as a product, a differentiation between the two are necessary in order to better understand the lifecycle meeting in this paper. Moreover, although the purpose of maintenance is the same – preserving the product so that it may fulfil its intended function at certain performance levels throughout its lifecycle – the scope and context of maintenance of products and production systems differs.

3.2.1 Product Maintenance

In general terms, the scope of maintenance within a product lifecycle is to preserve the function and performance of a single product or a set of similar products. The context of product maintenance is typically that 1) the manufacturer, 2) a third-party service provider, or 3) the end user is responsible for maintenance. The two former emphasize “sale of use”, i.e. Product-Service System, and the latter emphasizes “sale of product”. A typical example of product maintenance is that of an aero jet engine, where maintenance is planned and executed for a set of similar jet engines. Such products typically provide the same functionality throughout the lifecycle and have similar component interactions and degradation patterns. Hence, the associated needs for maintenance are likely to remain static. Takata et al. (2004) pioneered the modern view of maintenance that builds upon a lifecycle perspective where maintenance is integrated with product design through feed forward and feedback loops. Feed forward refers to the ability of maintenance management to adapt to changes throughout the product lifecycle, and feedback refers to utilizing the knowledge from maintenance to continuously improve the product design. To realize these two loops in practice, integration of information needs to be established between late (maintenance) and early (design) phases. The feed of maintenance information, e.g. degradation patterns, back to the early phases is a prerequisite for effective maintenance of future products (Roy et al., 2016).

3.2.2 Production Maintenance

The scope of maintenance within a production system lifecycle is to preserve the collected function and performance of an arsenal of similar and dissimilar products (i.e. production equipment). The context of production maintenance is typically that equipment is purchased from a wide selection of vendors, and the local maintenance organization is responsible for maintenance of all equipment within the plant. For example, a variety of welding, machining, and robotic equipment. However, instances of product maintenance do occur (as described in section 3.2.1), e.g. when vendors or service providers are responsible for the maintenance of certain equipment. While a production system typically evolves throughout its lifecycle, for example due to the introduction of new product variants that induce the need for certain functionality in tools and equipment or alters component interactions and degradation patterns, the associate needs for maintenance are likely to change over time, i.e. they are dynamic. Production maintenance practices therefore need to evolve in accordance, and Takata et al.'s (2004) feedback and feed forward loops are thus applicable to production systems. Unfortunately, the need to change or adopt maintenance practices when introducing new equipment (feed forward) is often overlooked in manufacturing companies (Swanson, 1997). Therefore, much research has focused on integrating production maintenance and production system development. Production systems can be improved by utilizing knowledge from maintenance of existing systems and apply it early phases (feedback) (Tsang et al., 1999). In practice, however, Sandberg (2013) claim that maintenance seldom is responsible or even involved in early phases of production development, where a reason for the limited use of the feedback loop is the lack of integration of maintenance information with other parts of the organization.

4 PRODUCTION MAINTENANCE IN PLATFORM CONCEPT DEVELOPMENT

To date, the lifecycle meeting involving production maintenance and platform concept development has been unexplored. To describe this meeting, a theoretical perspective is provided. To illustrate the meeting in practice, a case example from a jet engine manufacturer is provided.

4.1 A Theoretical Perspective: Complexity and Lifecycle Cost

To understand interfaces between products and production systems, ElMaraghy et al. (2012) argue that is it essential to study how complexity propagates from product life phases to production life phases. In addition, the associated cost for this propagation is an important factor to consider because increasingly complex products and production systems are linked to higher costs. Therefore, to describe the lifecycle meeting from a theoretical perspective, two examples are provided: 1) complexity, and 2) lifecycle cost (LCC).

To explain the context of these examples, product and production system complexity needs to be defined respectively. There exists no general consensus on the definition of complexity (ElMaraghy et al., 2012), yet the primary focus of this paper is variety-induced complexity. Hence, product complexity is defined as increasing number of variants (i.e. a product family have higher complexity than a single product), and production system complexity is defined as increasing plurality and variety of production equipment and their independence and dynamics. Taking the viewpoint from production, also production system capability needs to be defined. Here production system capability refers to the ability to produce a set of product variants and successfully fulfilling their individual requirements respectively. This capability is made up of a set of production resources, namely the infrastructure (including the equipment) and the employees (including their knowledge) (ElMaraghy et al., 2013) Specifically, this paper focuses on capability in terms of the equipment function and performance necessary to produce products that meet a wide range of customer needs.

In terms of complexity, the link between product design and production systems is well established: higher product complexity leads to higher production system complexity (ElMaraghy et al., 2012). Hence, variety-induced complexity influences both the product and its production system, and design engineers therefore need to consider the couplings across systems (ElMaraghy et al., 2013). Following this, higher production system complexity is likely to result in a wider range of production disturbances, and will therefore require greater levels of knowledge and training within the maintenance organization (Swanson, 1997). In fact, the capability of a production system is dependent on the maintenance organization's ability to preserve equipment function and performance over time. In essence, maintenance directly supports repeatable production processes that can produce a wide range of products within specified quality parameters (Sandberg et al., 2014). This example illustrates that decisions made in early phases of product design may be linked to the occurrence of production disturbances that affect the maintenance organization's ability to preserve production system capabilities over time.

In terms of LCC, the link between product design and production systems is also well-established: increased product variety leads to higher production system costs. However, despite extensive research on linking product variety to costs such as acquisition, inventory, re-tooling, transport processes, and set-ups (ElMaraghy et al., 2013), little attention has been given to maintenance-related costs. A main challenge for quantifying the economic effects of product variety is the limitation of traditional cost accounting methods (ElMaraghy et al., 2013). This limitation is particularly disadvantageous for quantifying the effects of maintenance as the existing economic system does not support long-term

thinking, preventive actions, and inclusion of the risk of not performing maintenance (Sandberg et al., 2014). LCC has been proposed as an alternative method that better captures the economic effects of maintenance. Design For Manufacturing and Assembly (DfMA) methods can be applied for a family of products (Emmatty and Sarmah, 2012) to enable comparison of alternative designs, and thereby choose production processes that are economically viable. As such, integrated product development enables the financial outcome of the production system to be considered already at the product design phase. Further, up to 85% of the production system's LCC is tied in early phases of design (Ahlmann, 2002). The challenge, however, is that the cost outcome is more or less reverse, as most costs become tangible during the use phase of the production system. These costs are highly dynamic and largely consist of maintenance-related costs because of production disturbances (e.g. man-time, spare parts, cost of lost production, energy consumption, waste management) (Bengtsson and Kurdve, 2016). In fact, maintenance-related costs often constitute the largest portion of the total LCC (Sandberg et al., 2014). Unfortunately, these costs are commonly ignored during the early phases of production system development, despite that they can be included in LCC calculations and be evaluated by utilizing the maintenance organization's quantified knowledge, e.g. giving estimates and distributions for equipment reliability and breakdowns (Bengtsson and Kurdve, 2016). This example illuminates that decisions made during early phases of product design will tie LCC; the same LCC that largely consist of production maintenance-related costs.
The propagation of complexity and LCC from product life phases to production life phases provide a theoretical perspective on the interplay between platform concept development and production maintenance. This interplay is highlighted in black in Figure 1.

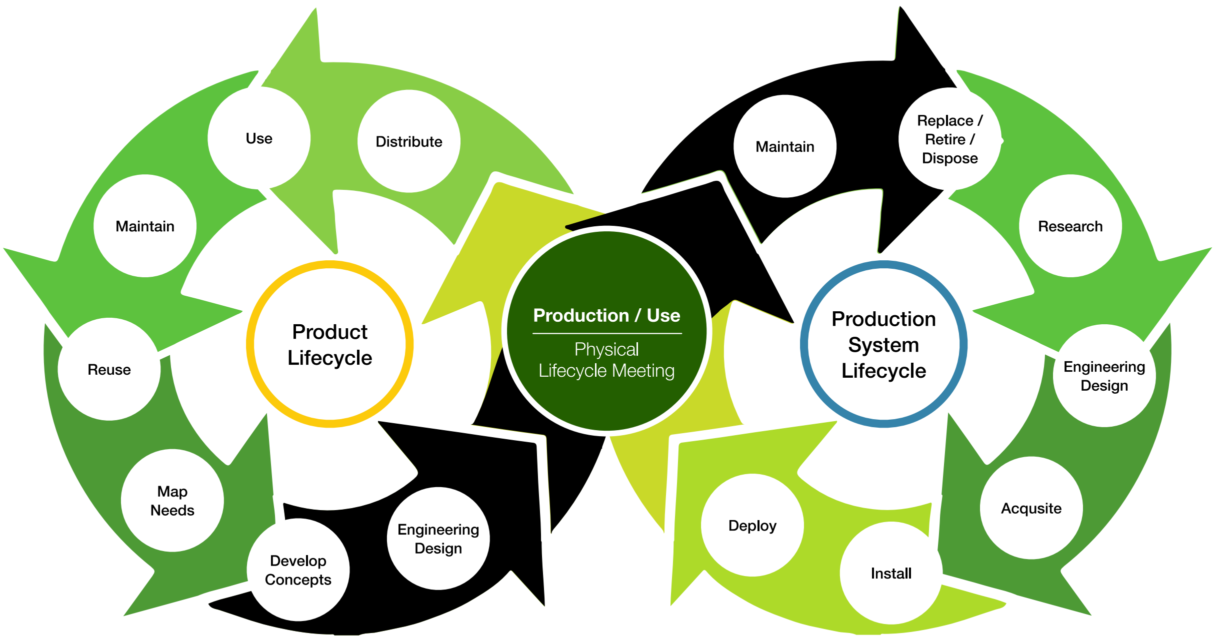

Figure 1. The interplay between platform development and production maintenance

4.2 Illustrating Case

To illustrate the propagation of complexity and LCC across platform concept development and production maintenance in an industrial context, a case from the aerospace industry is presented. The case company, GKN Aerospace Sweden AB, is an aero engine manufacturer that designs and manufactures components and sub-systems for commercial jet engines. The studied sub-system, a Turbine Rear Structure (TRS), is located at the rear of the engine and is illustrated in Figure 2 and Figure 3.

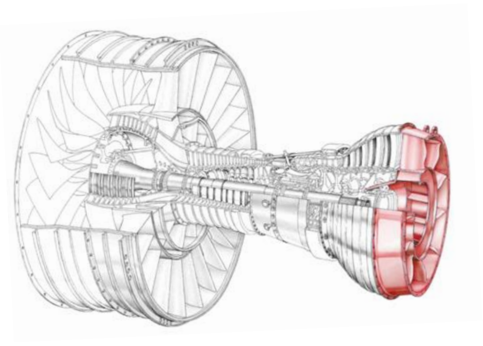

Figure 2. An aero engine with the TRS to the right (Levandowski et al., 2013)

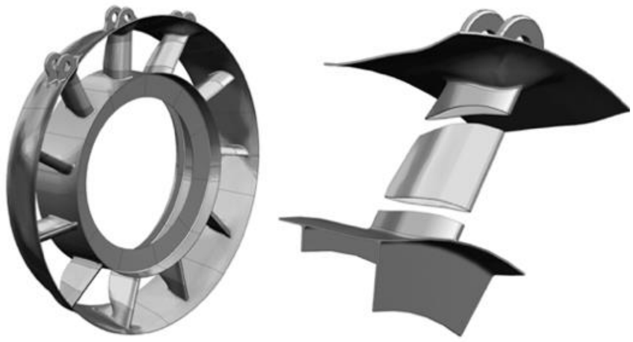

Figure 3. The TRS divided into segments, which are welded together in an assembly process (Landahl et al., 2016)

Five layers of complexity related to design and production of the TRS that serves the premise that complexity propagate from the product to production life phases are highlighted:

1. *Level of design customization*
   To comply with other systems of the engine architecture and serve the needs from jet engine OEMs, the TRS design is customized based on functions and performance on an engineer-to-order basis. Several TRS variants are therefore developed.
2. *The number of demanding design and performance requirements*
   Commonly, among the customized variants, the swirling air flow from the low-pressure turbine needs to be turned, the mechanical loads from the engine needs to be conveyed, and thermal loads needs to be reduced. The TRS is therefore designed as a complex integrated surface structure with highly demanding performance requirements.
3. *Producibility uncertainty*
   The design customization makes it difficult to ensure producibility of the TRS variants during the early phases of development when OEMs request quotes. For example, increased performance requirements often lead to higher demands on tolerances and more advanced materials.
4. *Production volume*
   The varieties of TRSs are currently produced at a yearly volume of a few hundred units. To manage the high customization and design complexity, the production system needs to be flexible enough to support the variety among the variants. Yet, to support economies of scale in production too, the flexibility must not increase the occurrence of production disturbances.
5. *Experience in using and maintaining production technologies (TRL level)*
   The experience of how to best utilize production technologies and the ability to preserve the function and performance of the arsenal of equipment may affect the occurrence of disturbances. The illustrating case is simplified by using Technology Readiness Level – TRL[1] (Mankins, 1995) – that enables differentiation between the experiences in utilizing a technology.

The case company has the ambition to reduce the time from a customer request to an offer of feasible conceptual design alternatives from three months to three weeks, whilst at the same time ensure producibility and, in the production phases, high productivity. To find producible conceptual design alternatives, an imminent uncertainty to undertake is how well a product variant may suit the current production system capabilities, and reveal if development work is needed to support e.g. design of new production tools.

The TRS can be produced in various ways and in different combinations; such as full cast, partly cast and partly welding; or partly cast, partly sheet metal pressing and partly welding. This example illustrates a welding assembly scenario, which is why the TRS is divided into segments, shown in Figure 3. To manage trade-offs between product performance and producibility aspects, several welding technologies can be explored based on the capabilities of each technology respectively. In fact, trade-offs will always need to be made to find feasible design alternatives. When designing the TRS, there are

1 TRL was developed by NASA to assess the maturity of a technologies

four welding technologies to consider: Tungsten Inert Gas (TIG), Plasma, Laser, and Electron Beam (EB) welding.

The capabilities of the welding technologies are typically considered static. Thus, the dynamics of the welding technologies is not considered in the early development phases, e.g. the ability to preserve the function and performance of equipment over time. Because of this, the information gained from producibility assessments may not be reliable enough to make credible cross product-production decisions during the early phases of platform development. As the welding equipment is used, performance levels will reduce due to e.g. equipment degradation. To preserve equipment function and performance over time and ensure repeatable processes that serves the production of TRS variants within specified quality parameters, continuous maintenance is required. However, the ability for the maintenance organization to preserve function and performance of the welding equipment will differ. Taking the TRS into consideration, “the effort to maintain” and the “LCC contribution” of the four welding technologies are provided in Table 1.

Table 1. The effort to maintain and the LCC contribution of four welding technologies

	Easy to maintain		Difficult to maintain	
High LCC contribution	**EB welding** □ Complex technology □ High acquisition cost □ Low failure rates □ Expensive repairs	*High TRL*: well-known technology, standardized equipment can be acquired, maintenance organisation has high competence and previous experience of the equipment, vendors can supply spare parts and maintenance programs based on their experience	**Laser welding** □ Complex technology □ High acquisition cost □ High failure rates □ High maintenance requirement □ Expensive repairs and calibration □ Spare parts for the unique tools need to be kept in-house to avoid extensive downtime losses □ Frequent preventive maintenance intervals	*Low TRL*: Equipment cannot be acquired as standardized equipment, little previous experiences of the equipment exist before start of production (neither within the local maintenance organisation nor the vendor)
Low LCC contribution	**TIG and Plasma welding** □ Both technologies similar maintenance requirements □ Low failure rates □ Short repair times □ Support with spare part and preventive maintenance programs from vendors	*High TRL*: well-known technology, can be acquired as standard equipment from a variety of vendors, extensive experience within the local maintenance organisation and vendors		

As shown in Table 1, the maintenance effort and the LCC contribution of the four welding technologies are vastly different. Differences include e.g. failure rates, repair times, internal and external experience and vendor support. These differences imply that the production system capabilities are not static, rather dynamic. Therefore, there is great potential to incorporate information of maintenance aspects in platform concept development to make more credible producibility assessments of the emerging TRS variants. Still, a challenge in taking cross product-production decisions is to manage the trade-offs between product performance and producibility aspects. For instance, while Table 1 indicate that Laser welding is not ideal from a maintenance perspective, it is instead favorable from a product performance perspective.

5 DISCUSSION

This paper highlights that production system capabilities are dynamic rather than static. This fact must be acknowledged to better support cross product-production decisions during platform concept development. The expected benefits of this include improved ability to minimize the negative effects of increasing complexity and its associated costs that propagate from product to production life phases. However, despite the need to ensure both producibility of product variants during early design stages and high productivity during the production stages, there is a lack of feedback and feed forward of necessary information across production and platform concept development. For example, an array of valuable information from maintenance exist that may serve this need, e.g. on equipment dependability and utilization, and maintenance-related costs. Using this information, design engineers may at an early stage be able to identify the need for further improvements within the maintenance organization, e.g. education and training, vendor collaboration, or spare part inventory.

In order to forge ahead, it is necessary to identify and discuss the enablers that are needed to realize this feedback and feed forward in practice. Based on the analysis in this paper, we identify at least three enablers that need to be addressed through further research and development of industrial applications. First, improved data management within production maintenance is needed in order to generate, store and use maintenance data within and across lifecycles. This includes continuous measurement of production equipment health parameters (e.g. vibration) to track degradation over time. Second, to transfer such information to design engineers, an IT architecture is needed to manage information sharing across product and production lifecycles. This refers to the horizontal integration of IT systems used in the different lifecycle phases, e.g. integration of the CMMS with PLM. Third, to use this information to support early producibility assessments, an integrated platform development methodology is needed, that takes dynamic production system capabilities into consideration. If these three enablers are realized, end-to-end engineering across product and production system lifecycles may be feasible. This seamless engineering allows for transparency across lifecycles, in which knowledge from production maintenance can serve the producibility assessments of product variants (feedback), and in which decisions during early product design stages can be verified in terms of their effects on later phases of the production system (feed forward).

6 CONCLUSION

This paper describes the interplay between platform concept development and production maintenance using a theoretical perspective and an illustrating case from the aerospace industry. The theoretical perspective is divided into two means that propagate through the product and production system lifecycles: 1) complexity, and 2) lifecycle cost (LCC). The illustrating case highlights five layers of complexity related to the design of an aerospace sub-system and the production technologies used to produce it. To emphasize dynamic aspects of the production system, the effort to maintain and the LCC contribution of four welding technologies are illustrated.

Based on this description, we argue that to make credible cross product-production decisions during the early phases of platform development, using e.g. trade-offs between product performance and producibility aspects, production system capabilities should be defined as the ability to produce an entire set of product variants. Further, these capabilities ought to be regarded as dynamic rather than static. Whilst static implies as designed, dynamic implies change over time. The dynamics of the production system capabilities are influenced by the production maintenance organization's ability to preserve function and performance of the array of equipment.

Three important enablers for improved integration between platform concept development and production maintenance are distinguished: 1) continuous measurement of production equipment health parameters to track degradation over time, 2) horizontal integration, IT architecture, between platform concept development and production maintenance, and 3) an integrated platform development methodology that supports the use of dynamic production system capabilities. The contributions of this paper form the basis for future research on how to ensure producibility of emerging product variants during early stages, as well as understanding the effects of an evolving product variety on a dynamic production system.

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