A METHOD TO CAPTURE AND SHARE PRODUCTION REQUIREMENTS SUPPORTING A COLLABORATIVE PRODUCTION PREPARATION PROCESS

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ABSTRACT

The production preparation process (3P) enables collaboration between design and production engineers during product development but its efficiency is limited by the abundance of documentation of manufacturing constraints and capabilities. Empirical studies showed that use of production requirements can increase the efficiency of 3P, however, the support for production engineers to capture and share production requirements is scarce. A method to support production engineers in identifying, defining, structuring and sharing production requirements and collaborating with design engineers is presented. The method has three major parts - focus areas and requirement categories, a worksheet for production requirements capturing and prioritization, and a workflow for using the worksheet. The method was developed in collaboration with practitioners and contributes to the existing knowledge by providing production engineers with a structured way of working with production requirements. Evaluation of the method in the case company showed its usability when developing product variants and that additional work is needed to support the development of new product families and assembly lines.

Keywords: Production requirement, Production Preparation Process, Design for X (DfX), Requirements, Integrated product development

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1 INTRODUCTION

The early process stages of product development are uncertain due to changing markets, technologies, policies and regulations (Han et al., 2020). Changing trends towards more customized products, emphasis on digitalization, sustainability and circularity, transportation challenges and pressures on cost, quality and time can drive a high mix of products and need for localised production (European Commission and Directorate-General for Research and Innovation, 2013; Isaksson and Eckert, 2020). Capturing and sharing knowledge across the product lifecycle with the design engineers, especially manufacturing knowledge, is needed to manage uncertainties (Gedell et al., 2011). It is essential to have access to the latest design and production information to manage uncertainties even if the information is sparse and incomplete in the early stages (Landahl et al., 2021). The shorter lifecycles of products and the increased number of variants have increased the importance of coordinated decision-making between product development and production (Brunoe et al., 2020). The Lean Production Preparation Process (Lean 3P) is used in the industries for this coordinated decision-making (Areth Koroth et al., 2021). The lean 3P consists of a series of workshops aligned with the product development process that promotes cross-functional collaboration and problem-solving (Coletta, 2012). The production preparation process uses design for manufacturing and assembly (DFMA), failure mode and effects analysis (FMEA) and lessons learnt to share manufacturing knowledge with design engineers and support producibility assessment (Areth Koroth et al., 2022). Dependence on the knowledge of individuals involved in the production preparation process and lack of information in the early phases as the product is not matured, reduced the efficiency of DFMA, FMEA and lessons learnt (Breiing and Kunz, 2002; Shehab and Abdalla, 2006). In a preceding study, it was identified that a structured way of working with production requirements was needed to support production engineers to identify, define and share production knowledge while supporting collaborative decision making with design engineers during the new product development process (Areth Koroth et al., 2022). Previous works were reviewed to identify the existing methods to capture and share production requirements during the product development process. The articles focussed on capturing the production knowledge in model-based, CAD-based approaches, PLM-based and ontology-based approaches (Canciglieri and Young, 2010; Hedberg et al., 2022; Rea Minango and Maffei, 2023; Urwin and Young, 2014). These approaches gave different methods to organize the production requirements but were limited in supporting the production engineers in requirement identification and structuring.

A research question was formed based on the needs identified from the industrial case study and review of previous works in literature to support production engineers to identify production requirements and use it for collaboration with design engineers during the production preparation process. The question was *" what method can support production engineers to identify, define, structure and share production requirements and enable collaborative decision-making during the production preparation process?"*. This paper presents the method developed to support production engineers to work with production requirements. The method has three parts- Focus areas to guide the production engineers to identify where the production requirements are needed, the worksheet for requirement setting and requirement analysis and workflow to use the method. The method is intended to support a structured identification of production requirements and decision-making through collaboration. The method was evaluated for usability and applicability in the case company through a workshop.

2 FRAME OF REFERENCE

The production preparation process provides opportunities for collaboration between design and production engineers and production requirements can support knowledge exchange in this process. This section describes the production preparation process, tools used to support in this process, challenges this process faces and reviews the existing works that have been done to capture production knowledge and production requirements.

The production preparation process (3P) aims at showing that the product is producible and it has four steps: information gathering, innovation, prototyping and rapid redesign and optimization (Coletta, 2012). The information-gathering phase is critical as it aims at understanding the problem being addressed through the design. Sources for information are products and process attributes, lessons

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learned and previous documents, and visual supports can aid in improving the effectiveness of this documentation (Coletta, 2012). Tools such as design for manufacturing and assembly (DFMA), lessons-learnt and failure mode and effects analysis (FMEA) are used to support production preparation (Areth Koroth et al., 2021). Though DFMA and FMEA were well-established concepts, their successful utilization during the 3P dependent on the knowledge and skills of the individuals involved in the process and working with production requirements can support information capture and collaboration between design and production engineers to ensure producibility (Areth Koroth et al., 2022).

Existing works that captured production requirements during product development were reviewed. Design for assembly first focuses on simplifying the product structure by reducing the number of parts and improving ease of assembly followed by design for manufacturing where detailed design for minimizing manufacturing costs is developed (Boothroyd et al., 2010). DFA2 is design for automated assembly including a set of guidelines such as the base object, tolerances, assembly directions, shape and level of defects to be considered during product design for automated assembly (Eskilander, 2001). Jiao et al. (2007) link the design parameters and process variables through a product family design approach. This is achieved through the process design task where production planning is done within the existing production capabilities. The concepts of manufacturing system function and manufacturing requirements have been suggested to support the formation of requirements specifications for products and processes and forward traceability of changes in product systems to manufacturing systems (Elgh and Sunnersjo, 2007). The manufacturing system function links product-related objects to production equipment so that design engineers can get information about the existing manufacturing options and associate aspects to consider in the development. Nafisi et al. (2018) grouped manufacturing requirements into three categories- physical properties of the part, assembly process and material handling and line feeding and identifies test assemblies, risk assessment, DFA and QFD as some of the tools to verify and communicate these requirements. Bix and Witt, (2020) suggest that introducing manufacturing constraints can increase the effectiveness of communication at the design-manufacturing interface. KPI parameters related to material, tolerancing, DFM and DFA will improve the production capability knowledge which can be then used in the concept development phase. Rea Minango et al. (2022) categorize the requirements to support assembly planning into the primitive level (feed, move, grasp, mount), part level (tolerances, geometric relations), product level (sequencing, accessibility, scheduling, stability, operation) and batch level (tool exchange, parts feeding, transport, ergonomics). There has been research on capturing manufacturing information in model-based engineering and model-based manufacturing through the use of product manufacturing information in CAD and product lifecycle management (Canciglieri and Young, 2010; Urwin and Young, 2014; Hedberg et al., 2022). Silva et al. (2019) presented a tool for integrating automation requirements into the conceptual product design phase. Chang et al. (2010) presented a method for the development of ontologies to be used in DFM. Urwin and Young (2014) presented a method for manufacturing knowledge capture using knowledge document templates for machining and inspection knowledge which were then shared in a PLM environment.

The review of existing works identified different methods to capture manufacturing knowledge and concepts that can be used as production requirements. However, there was a need to support the production engineers to identify, define and structure the production requirements. Also, the support should enable discussions and decision making when working with production requirements. The method described in this paper is intended for that purpose.

3 CASE COMPANY AND METHODOLOGY

This work is part of a 3.5-year collaboration project focussing on design for producibility and production preparation. The design research methodology framework (Blessing and Chakrabarti, 2009) is used in the overall research work and this paper presents the results of the prescriptive study following the results from the research clarification (Areth Koroth et al., 2021) and descriptive study 1(Areth Koroth et al., 2022). The case company in this study produces outdoor power products following a select variant production strategy. They have a global presence with 28 manufacturing locations and around 14000 employees. Analysis of the current production preparation method showed that they use the lean3P process aligned with the company's NPD process. The 3P process consists of

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four workshops where the stakeholders meet and assess producibility. Not having the requirements at the right level of detail, lack of prototype at early stages, communication gaps and dependence on individual knowledge were challenges faced while using these documents and methods during the production preparation process (Areth Koroth et al., 2022). A cross-functional team was formed within the case company to support the concept development process for the method of working with production requirements. The development process was iterative with the initial focus set through a workshop with different stakeholders within the company, then the development of the concept with support from assembly observation and literature study followed by evaluation and improvement through discussion with the team. Table 1 summarizes the activities conducted during this study.

Table 1. Details of activities carried out during this study

Activity	Purpose, Method and Participants
Workshop 1- Scope setting	Aim: State of practice and setting the scope of the concept development Content: Discussion on production requirements- content and challenges, vision, challenges and ideas for the method. Participants: Systems engineer, Project manager manufacturing, Project manager PLM, Lead engineer, Design engineer How: Notes on post-it notepads, Audio recording of the discussion
Observation	Aim: Setting the scope and identifying focus areas Participant: Project manager manufacturing How: Assembly line observation and observation notes
Method Development	Aim: Develop the method Participants: Project manager manufacturing and Project manager PLM Method: Brainstorming, literature study, discussion
Workshop 2 - Evaluation	Aim: Evaluate the usability and applicability of the method and identify areas of improvement Content: Discussion on usability and applicability of the method in identifying, defining, structuring, sharing and collaborating between design and production engineers. Participants: Project manager manufacturing, project manager PLM, lead engineer, design engineer and systems engineering manager How: Notes on post-it notepads, Audio recording of the discussion

4 PRODUCTION REQUIREMENTS - CURRENT STATE AND TARGET

The first workshop focussed on understanding what production requirement is according to the participants, what is the vision of using production requirements and what are the challenges and opportunities while using production requirements. The result of the workshop is summarized below.

- Production requirements are dependent on the process stage at which it is used and include aspects such as automation levels (manual, semi-automatic), lists linking components and production systems, interfaces such as gripping points, requirements on equipment, dimensions, and ergonomic aspects. Challenges faced in the current state of practice are working in silos, lack of alignment between product and production development, lack of clarity on stakeholder responsibilities, and standardizing and finding the requirements.
- Vision with the use of production requirements is to include the production requirements in the requirements-based development process, support early dialogues between production and R&D, follow good sustainability practices for people and environment, same requirements for all the sites, well-defined storage space for the requirements, avoid late changes of the product due to missing information, reuse of interfaces, to optimize the use of existing production capabilities and to add new capabilities when and where needed. Ideas for overcoming the challenges were to implement the requirement-based development ways of working, standardization and categorization of production requirements (types, characteristics, level of detail and when in the process are they to be addressed), starting to shape the manufacturing system early and visually in a system while linking it to the product, development of a common model of the product and production system which can be worked on by employees from both design, manufacturing and

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maybe additional stakeholders and to run a pilot on requirement based development with production requirement.

The workshop set the focus for the development activity for the method to work with production requirements. The support developed should be easy to use and understand, usable at low product maturity, evaluate consequences of not meeting the requirements, prioritize requirements and be at the right level of detail for the requirement depending on the development phase.

Following the workshop, an observation of a semi-automated assembly line producing engines was conducted for identifying the production requirement areas. The assembly process consisted of three stages- two fully automated and one semi-automated. There were quality inspection stations in between. Automated assembly assembled the components such as crankcase and piston assemblies with operations such as pick and place, pressing and screwing. It was important in this operation to have proper loading of parts as improper loading can lead to quality issues and line stoppages. There was no conveyor and had piece flow. The semi-automatic assembly was for assembling flexible components such as throttle lines, fuel lines, and cable assembly as it was difficult to have automation for flexible components. Screwing operations in this stage was done with the help of robots. Figure 1 below shows a schematic representation of the assembly line observed. This observation was used to identify the focus areas for the production requirement identification which is discussed in section 5.1.

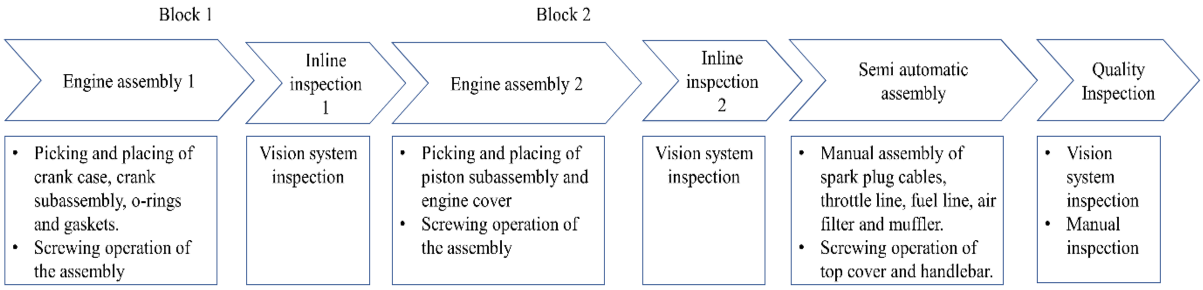

Figure 1. Representation of the observed assembly line

5 METHOD FOR WORKING WITH PRODUCTION REQUIREMENTS

The developed method aims to support identifying, defining, structuring, and sharing of production requirements to support design for producibility during production preparation. This method includes three parts: focus areas and requirement categories, the requirement worksheet, and the suggested way of working that can guide the production engineers to review the components that are assembled and list requirements in the areas critical to production. These requirements are then discussed between the design and production engineers.

5.1 Focus areas and requirement categories

The first part of the method supports the production engineers to identify the production information relevant to design engineers using six focus areas and a list of ten requirements related to these six areas. The focus areas and requirement categories are given in Table 2 and represented in Figure 2 and are perceived as general enough to support any assembly process and can be expanded if needed to suit a particular assembly process. The first four requirements relate to the interfaces where the product components and the production systems interact. The design of the base object is critical as it forms the base for the subsequent operations. According to DFA2 (Eskilander, 2001), the base object is the first part that is assembled. It should be designed in such a way that further components can be assembled without the need for additional fixtures. Also, changing the assembly fixture is one of the major costs in the assembly line. So it is important to consider interface requirements on the base object to both the assembly fixture and other components. The next requirement is how the machine interacts with the components. This relates to the gripping surface guideline in DFA2. The component packaging is the interface where the components are loaded into the machine. It is important for proper orientation, preventing tangling and hooking. Process constraints aim to identify the constraints that the design engineers need to be aware of while designing the product. There can be some

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requirements that need to be considered for a particular operation to benefit the subsequent operations. These can be related to tolerance stacking, surface roughness or assembly sequencing for example. This requirement aims to identify any such requirements that need to be considered. Some requirements need to be placed on the product design to support quality testing and certifications. The quality requirements are for identifying such requirements. Requirements for process stability/machine performance are for increasing the accuracy of the operation and thereby quality eg: countersinks and chamfers which can guide the assembly. The safety and ergonomic requirements are those which are needed to provide a safe and healthy work environment for human operators.

Table 2. Focus areas and requirement categories

Focus areas	Requirement Category
1. The interface between the base object and assembly fixture	1. Base object to assembly fixture
2. The interface between the base object and component (Base object as the assembly fixture)	2. Component to Base object
3. The interface between the base object/component to the machine	3. Machine to Component/Base object
4. Interface for loading the components to the machine	4. Component Packaging and loading
5. Machine Capabilities	5. Process constraints
	6. Machine performance/Process stability
6. External Factors	7. Quality requirements
	8. Requirement from the next operation impacting design in this operation
	9. Safety Requirements
	10. Ergonomic requirement

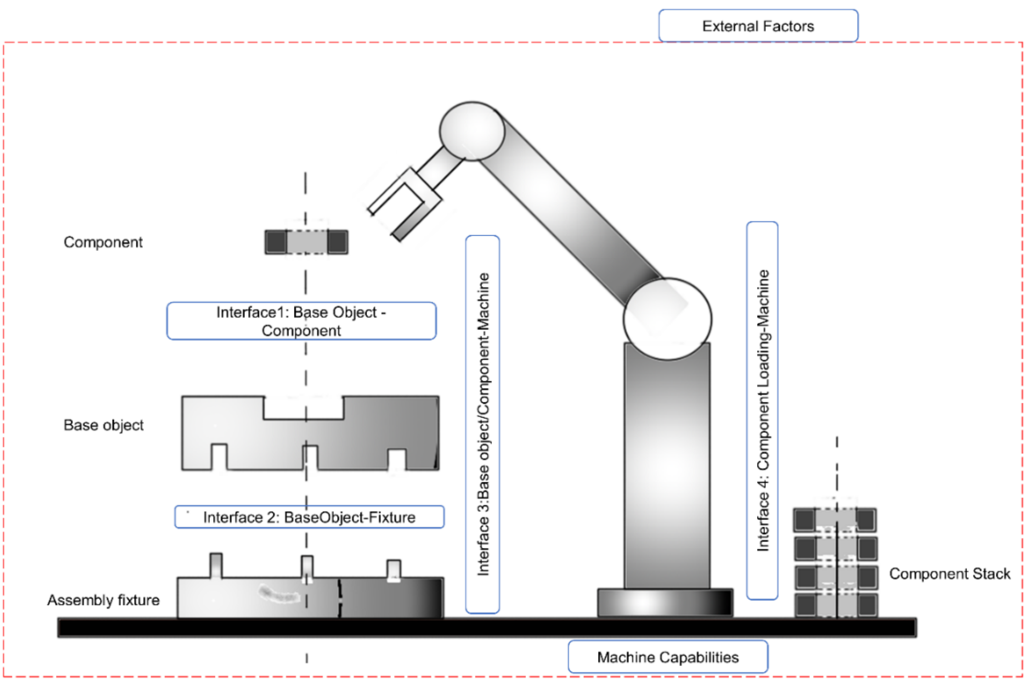

Figure 2. Production requirement areas

5.2 The Requirement worksheet

Each requirement listed above was defined as a requirement object with certain attributes which are captured in the requirement worksheet as shown in Figure 3. Requirement description is done using the functional description method to represent the requirements in a basic form. This can enable more design freedom and innovation while keeping within the production capability. The next attribute is manufacturing rationale to capture the need for the requirement. It was identified that the production

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requirement should also have a link to reference product/solution and image to make the requirement clear. There is also a provision for capturing the consequence of not fulfilling the requirement. The requirement readiness levels will enable the identification of how much work is needed to fulfil the requirement by clarifying if the current solution can be used as is or needs modification or an entirely new solution. Requirement prioritization is done based on the MoSCoW analysis (Clegg and Barker, 1994) which allows the requirements to be categorized as must-have, should have, could have and won't have. This is followed by the action plan for the requirements and traceability aspects like version, date and responsibilities.

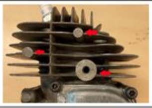
Production Requirements Decision Support												
Document date			dd/mm/yy						Version:	1		
Document Owner			Production Engineering									
Requirement Setting								Requirement Analysis				
Sl No	Component	Production Requirement Category	Requirement description	Manufacturing rationale	Reference Solution	Images	Consequence	Priority	Requirement readiness level	Action	Responsibility	Updated on
1	Component A	Base object (as a fixture)/Base object-Component	Hold gasket in place	Orienting pins to prevent quality issues during assembling	CompA_001		Time, quality, cost	Must have	Use as-is			
2	Component B	Baseobject - assembly fixture	Well defined fixture points on a drawing	To avoid remaking fixtures. Need on the drawing- to prevent fixture change within project	CompB_001		Time, cost	Must have	Needs modification			
3	Component C	Machine to Component/ Base object	Well defined surfaces to grip with measurements in drawing.	To use exisiting grippers.	CompC_001		Cost	Should have	Use as-is			
4	Component C	Quality requirements	Space requriements for pressure testing	Enough space around spark plug to reach with pressure test	CompC_002		Quality	Should have	New			

Figure 3. Sample requirement worksheet

5.3 Suggested workflow

The workflow for the production requirement elicitation is given in Figure 4. When a new project is started, the project management team decides if the product is a new product family or a variant of an existing product. In both cases, the production support decision sheet can act as a knowledge asset. The product concept is then given by the product designers to the production engineers who evaluate the design, select the processes and ask which requirements are needed for that component. The production engineer evaluates the components based on the requirement categories and requirement attributes and records the production requirements in the sheet as shown in Figure 3 in section 5.2. This is then shared with the design engineers. A cross functional team involving design and production engineers the requirements and formulates an action plan. This document then can be used to support the 3P workshop as well as other DfX and FMEA activities.

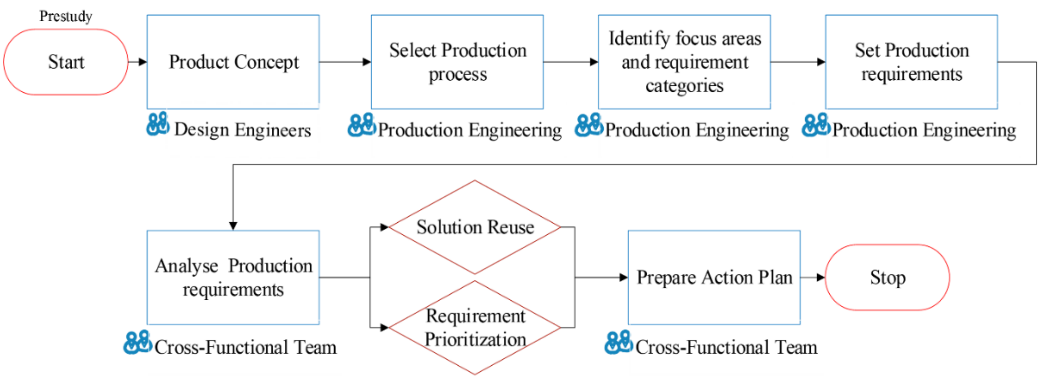


Figure 4. Suggested workflow

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6 EVALUATION OF THE METHOD

An evaluation workshop with five participants from manufacturing, design engineering, systems engineering, and product lifecycle management departments was conducted. The duration of the workshop was three hours with two sessions. The first session focussed on presenting the method to the participants and during the second session, the participants were asked questions about the applicability and usability of the method. Usability evaluation identified that the method was easy to understand, and it provided the opportunity for collaboration and knowledge reuse as it used a standard sheet. Capturing the rationale for the requirements, images of existing solutions and requirement prioritization contributed to improving dialogues between design and production engineers. This method is applicable when working with a matured product concept and variants of the same product family but needed improvement to work with products that are not matured. It should be possible to define requirements on different levels such as project, product, system and component. The requirement should also take into consideration the difference in cultures and processes in different production locations. The method should consider how the requirements can be stored and shared. It is also important to define the roles and responsibilities of the people involved and when the requirement identification and analysis activities are carried out.

7 DISCUSSION

New product development is characterised by uncertainties and collaboration between design and production engineers can help to overcome these uncertainties. Empirical studies conducted as part of the research work identified that there is a need to support the production engineers to identify and structure the production requirements that are needed for the design engineers so that the design and production engineers can collaborate and take decisions together. The work presented in this paper aimed at answering the research question " *What method can support production engineers to identify, define, structure and share production requirements and enable collaborative decision-making during production preparation process?".*

The method supports identifying the production requirement using the focus areas and requirement categories. The focus areas are based on the DFA2 (Eskilander, 2001) guidelines and product-production interfaces identified during the assembly observation. This is intended to guide the manufacturing engineers to think about where the requirements are needed. These focus areas are linked to the requirement categories in the worksheet. The requirement categories in the method are flexible enough to include previous work such as process variables (Jiao et al., 2007), manufacturing system functions (Elgh and Sunnersjo, 2007), manufacturing requirements (Nafisi et al., 2018), key performance indicators (Thompson et al., 2018) and assembly requirements (Rea Minango et al., 2022). The focus areas and requirement categories are not process-specific and new requirement categories can be added to the focus areas if needed. Dick et al. (2017) state that the support for requirements management must allow for a well-defined requirement statement while providing the opportunity for analysis and improvement. Also, a requirement should identify a process or product´s operational, functional or design characteristic or constraint, and should be unambiguous, testable and traceable. The method for working with production requirements fulfils this by using functional description to define the production requirements. Additional information such as manufacturing rationale, reference projects or solutions, images and consequences help in removing ambiguity in the production requirement definition process. The method supports the structuring of the production requirements through prioritization and the use of the worksheet. The use of must-have, should-have, could-have and won't-have to prioritize the production requirements would allow the prioritization process to be simple to use for the participants in the production preparation workshop. This will allow overcoming the challenges of prioritization during requirements management identified by Song et al. (2018). The requirement readiness levels will enable to identify of how much work is needed to fulfil the requirement by clarifying if the current solution can be used as is or needs modification or an entirely new solution. Thus, it will help in production preparation in practice, by providing a structured requirement list to initiate discussions and capture knowledge.

The method can support design for manufacturing and assembly, design for automated assembly and failure mode and effects analysis methodologies by converting the design guidelines in these

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methodologies into requirements and acting as a common knowledge base for them. This can save resources in the early development phases where the product maturity is low to use the DFMA and FMEA but still consider their requirements. Also, an attempt to identify the interfaces between the product and production systems has been made that can support decisions concerning the co-development of product and production systems. Thus, the presented method can improve communication and collaboration between design and production engineers.

An evaluation of the method was conducted in the case company to check usability and applicability. Future work will be based on the identified areas of improvement such as having requirement levels based on product maturity and cross-case testing in companies in other fields such as automotive and house building. Also, the applicability and support in knowledge transfer during greenfield development can be tested. Using production requirements to develop product-production interfaces and requirement management in a PLM environment are other possible future works that are interesting to pursue.

8 CONCLUSION

The production preparation process provides a collaborative environment where the stakeholders can come together and take decisions on product and production development. The efficiency of this process can be improved using production requirements. Empirical studies identified a need for a structured method to support production engineers to specify and collaborate while working with production requirements. This paper presented a method for identifying, defining, structuring and sharing production requirements. The method has three parts- focus areas and requirement categories, a worksheet that supports capturing production requirements with rationale and consequences, taking decisions such as requirement prioritization and solution reuse and an action plan for fulfilling the requirements, and a workflow for using the worksheet. This method encourages structured communication and knowledge sharing between design and production engineers. The method was evaluated in the case company for usability which showed that it was usable while developing product variants but needed improvement to support new product families and assembly lines.

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