INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.22

Aligning production requirements with product and production maturities: enhancing production preparation during product development

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Abstract

Product development is multidisciplinary with high uncertainties necessitating coordinated decision-making between design and production. This paper presents a method to work with production requirements to support production preparation during product development aligned with different product and production maturities. The work was conducted in collaboration with two global manufacturing firms. The method supports identification, definition, and structuring of production requirements and the collaboration between design and production engineers for requirement prioritization and follow-up.

Keywords: *product development, integrated product development, requirements management, production requirements, production preparation process*

1. Introduction

The product development process is a complex engineering process that involves different disciplines and emergent behaviour (Simpson and Martins, 2011). Factors such as high product variety, uncertainty in markets, shorter lead time and sustainable manufacturing leading to reconfigurable and changeable manufacturing systems have necessitated coordinated decision-making between design and production domains (Brunoe et al., 2020; Skärin et al., 2022). Integrated product development supports interaction between product and production domains throughout the product lifecycle (Albers et al., 2022). Andreasen and Hein (2000) presented the integrated product development (IPD) process model to integrate the required activities marketing, design and production departments must perform, as their alignment is essential for a company's success. Process models such as product-production codesign (Albers et al., 2022) and integrated product and process model (Vielhaber and Stoffels, 2014) have been proposed to support IPD. Focus has been given to model-based systems engineering to support the early phases of product development and create a common language between the product and production domains (Albers et al., 2022; Schäfer et al., 2023). Setti et al. (2021) presented a five-step process model to support IPD by associating value engineering and design for automation. IPD by Andreasen and Hein (2000) highlighted the importance of the production preparation phase in proving the producibility of a product. Literature on production preparation focuses on technical production preparation tools such as computer-aided design, process planning and manufacturing (CAD/CAM/CAPP), product lifecycle management (PLM), computer-based design for manufacturing, methods-time measurement analysis and enterprise resource management (ERP) tools (Duda, 2020; Lukić et al., 2010; Markov et al., 2021). Lean-3P is a production preparation approach that allows for product and production development concurrently and is used as a production tool (Coletta, 2012; Ramakrishnan and Testani, 2011). The efficiency of simultaneous engineering and design for manufacturing can be improved by supporting

the storing and reusing of product and production system knowledge formally (Albers et al., 2022). However, a lack of support for production engineers has been observed in structuring and sharing their requirements in a common language, as that of design engineers (Areth Koroth et al., 2023). Hence, methods and tools that facilitate the use of a common language between the design and production domains to clearly present their requirements and measure the evolution in the maturity phases are required (Ferreira et al., 2021). Working with production requirements can support production preparation during the early phases of product development (Areth Koroth et al., 2022).
This paper presents a method for working with production requirements aligned with the product development process and considering different product and production maturities. It builds on previous study by Areth Koroth et al., (2023). The research question that guided this work was, "How can the method to work with production requirements be aligned to the product development process and varying product and production maturities?" Data collection was conducted in two companies to understand product and prototype maturities at various product development phases. This helped align the method of working with production requirements with the product development process.

2. Frame of reference

Requirements have various uses during product development (PD) such as identifying customer needs, setting target specifications for the product and using it to prune concepts during development phases (Ulrich and Eppinger, 2012). Hence, considering stakeholder requirements along with customer requirements in the PD project remains essential (Stolt and André, 2022). Production requirements support producibility assessment during systems analysis and the support for requirements management must allow for a well-defined requirement statement while providing the opportunity for analysis and improvement (Walden et al., 2015). These requirements can be managed through IT systems; however, they have varying degrees of formalisation (Stolt and André, 2022).
Areth Koroth et al. (2023) presented a method for working with production requirements. The method has three parts- identifying the focus areas and requirement categories, worksheet and a workflow for using the method. Focus areas and requirement categories support the identification of production requirements. The worksheet captures information such as product details component/module, process, requirement category, requirement description, manufacturing rationale, reference to existing solutions and consequences of not meeting the requirement, which supports defining and structuring production requirements and collaboration with design engineers for requirement analysis, prioritisation and action plan preparation. However, this method lacks support for managing different product and production maturities and for a detailed alignment with different product development phases.
Maturity measurement systems such as technology readiness levels (TRL) and manufacturing readiness levels (MRL) have been used to measure readiness of technology development and manufacturing during product development. Technology readiness levels can be defined as a systematic measurement system to assess the maturity of a particular technology which was introduced by NASA and manufacturing readiness levels measure production capabilities (DOD Handbook, 2018). Both TRL and MRL go hand-in-hand to measure the risks in a product development project (ibid.). Technology readiness and manufacturing readiness levels have also been used for integrating product development and production. Ferreira et al., (2021) presented a development model for supporting product innovation by combining TRL, MRL and design for manufacturing and assembly (DFMA). Ward et al., (2018) state that the term capability is suited for describing maturity in a manufacturing setting as success is not just dependent on technology but also on operational, commercial, organisational and integration issues. Webster and Gardner (2019) identified that TRL fails to consider the context change that happens in a project. Jesus and Chagas Junior (2022) presented a method to measure integration readiness level to complement the TRL methods.

3. Study design

Two companies were selected for data collection based on their product portfolios and their participation in the previous studies. The details of the case companies and data collection are given in Table 1 below. Data collection was conducted to understand how to align the production requirement specification method with product and production maturities in different product development (PD) phases. A study of the PD processes in the case companies was conducted to identify product maturity, activities carried out by product development and production departments and documents and tools supporting production preparation during the different product development phases. This was complemented by conducting interviews with design and production engineers involved in product development projects. The method was improved based on the collected data. Evaluation workshops, including an individual questionnaire, were conducted at both companies to check the usability and applicability of the method.

Table 1. Details of data collection activities

		Company 1 (C1)	Company 2 (C2)
Company information		Product: Outdoor power products	Products: Automotive supplier and consumer products for active living
		Employees:14000	Employees: 3300
		Locations: 28 (global)	Locations: 9 (global)
Activities	Interview	Group manager (Project management office-Manufacturing), project manager manufacturing, design engineer, manager-R&D	Director of operations development, chief engineer, manager-R&D, project manager-production engineering
	Document study	Product development process	Product development process
	Workshop	Group manager (Project management office-Manufacturing), project manager manufacturing, design engineer, manager-R&D	Director of operations development, chief engineer, manager-R&D, project Manager-PE, global director of design engineering, PLM and digitalization Specialist

4. Case study results

This section summarises the findings obtained from the data collection in the case companies from both the interviews and document studies.

C1 mostly works with the variant development of existing product families with the carryover of modules. A separate department is involved in innovation projects. The product development (PD) process in this company starts with the planning phase, in which market and user requirements are created and assembly allocation and make/buy decisions are made. Depending on the project, input for this phase can be derived from either the pre-development team or the marketing department. C1 uses TRLs to measure the maturity of the systems and sub-systems. TRL4 is expected in the pre-study phase. There is a pre-prototype (commonly 3D printed) in this phase which may not be the final model but has representations of the systems and can be used to initiate producibility discussions among the design team, production team and other stakeholders. The planning phase is followed by the concept phase, in which all inputs from the planning phase are analysed and requirement specifications and product concepts are created. The TRL is at 5 and prototypes have the correct materials. This is followed by separate system-level and detailed design phases in which CAD models are created and finalised. There is increased production involvement through project team meetings, production preparation process (3P) workshops and review meetings. Next is the industrialisation phase, in which production equipment and tools are purchased. A mature production concept has been formed by now and pilot productions are executed for both engineering and manufacturing testing. In these stages, the product concepts are fully matured. The progress is evaluated at the gates between the phases, and 3P workshops are run simultaneously with the PD process.

C2's PD process consists of planning, concept development, design, production engineering and production phases, including gates in between the phases to evaluate the progress. Planning in C2 focuses on business case development for the product, product concepts are developed in the concept phase and concepts are converted to production documents in the design phase. The production engineering phase aims at tooling and ordering production equipment. In the production phase, production ramp-up is carried out. Like C1, there is a pre-development department that investigates new products. Successful ideas from this pre-development phase are transferred to the concept development

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phase. Input for the concept development phase comes from marketing and pre-development departments. Commonly, there is a printed prototype in this phase or at least a design intent. Pre-development projects have higher maturity when it reaches the concept phase. Production involvement in C2 begins at the end of the concept phase and is high during the design phase. But in the design phase, the concept is converted into a production document and has higher maturity and lower flexibility. There are prototypes in the concept and design phases. The concept phase prototype is not functional but can be used to initiate producibility discussions while design phase prototypes have high maturity levels. At the end of the design phase, the design is frozen, and in the production engineering phase, orders for tooling and equipment are released. This company does not use TRL to indicate maturities but has readiness checks at the gates. There are no formal production preparation methods in place; however, the DFMA checklist is used to support this activity.
The results of the data collection are summarised below.

- Innovation projects are managed by dedicated departments and are separate from the product development processes at both companies.
- This results in products with higher maturity when entering the concept development phase.
- The design and production engineering teams were not involved in these innovation projects; however, the interviewees expressed that production requirements could guide development.
- In C1 there are separate system-level design and detailed design phases after the concept phase while C2 has longer concept phases and design phases. Product architecture and interfaces that influence production are decided in the system-level design phase. C2's longer concept phase can result in the late involvement of production personnel, by which time critical decisions regarding product architecture and interfaces are made.
- A lack of production personnel exists in the early phases of product development, and the production requirement document can be a knowledge asset.
- Technology readiness levels are used at C1 (not C2) to assess the maturity of the different sub-systems. Manufacturing readiness levels are not used in either company.
- Carryover of systems and sub-systems is common, which allows the reuse of existing knowledge of production processes to create initial specifications of production requirements.
- Prototypes in the concept phase focus on the functionality of individual systems and can be used for production preparation.

5. Production requirement specification method

The first version of the production requirement specification method was developed to support production engineers in identifying, structuring, defining, and sharing production requirements and collaborating with stakeholders such as design engineers (Areth Koroth et al., 2023). Its successful implementation relies on the alignment of product and production maturities and the product development process. Three scenarios were identified to align the method with the maturities. These are existing product-existing/new production line, variant product-existing/new production line and new product-existing/new production line as described in Table 2. These categories vary from high knowledge/low flexibility to change to low knowledge to high flexibility to change. The data collected during this study were used to strengthen the method to support these different scenarios.

Table 2. Scenarios for production requirement application

		Production	
		Existing	New
Product	Existing	Introducing existing products in existing production lines.	Introducing existing products in new production lines
	Variant	Introducing new variants of existing products in existing production lines.	Introducing new variants in a new production line
	New	Introducing new products in existing production lines.	Introducing new products in a new production line.

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5.1. Method improvement

Analysis of the data collected showed systems and sub-systems carryover as well as production process knowledge in new projects. In addition, TRL can be used not only for design engineers to decide the system maturity but also for production requirement prioritisation and deciding if it should be constrained or guideline. The worksheet presented in Areth Koroth et al. (2023) was extended to capture information about the process and project phases were added to support an understanding of when production requirements were finalised in the previous projects (see Figure 1).

Requirement Setting											Requirement Analysis							
Sl No	Product Type	Product Number	Component/ Module	Production Requirement Category	Requirement description	Process	Manufacturing rationale	Reference (product/ solutions)	Images	Consequence	Priority	Requirement readiness level	Action	Responsibility	Finalised in Project Phase	Status	Updated on
1	Saw	1	Comp A	Base object (as a fixture)/Base object-Component	Hold gasket in place	Pick and place Robot	Orienting pins to prevent quality issues during assembling	chainsaw_1_gasket_orientation		time, quality, cost	Must	Use as-is	Orienting pin with dimensions to be added in drawing and Controlled in pFMEA	Design engineer/ Production Engineer	System level design	In progress	
2	Saw	1	Comp B	Base object (as a fixture)/Base object-Component	Orient part on the base object	Pick and place	Orient part on the base object during assembly to guide on to the correct location	chainsaw_1_component_orientation		time, quality, cost	Should	Use as-is	Orienting pin with dimensions to be added in drawing and Controlled in pFMEA	Design engineer/ Production Engineer	System level design	In progress	
3	Saw	1	Comp B	Baseobject - assembly fixture	Well defined fixture points on a drawing	Pick and place	To avoid remaking fixtures or reuse the same production line.	chainsaw_1_base object_fixture orientation		Investment cost	Could	Needs modification	Part dimension varying. Same requirement defintion but new values	Design engineer/roduction Engineer	Concept	Complete	
4	Saw	1	Comp C	Machine to Component/Base object	Well defined surfaces to grip with measurements in drawing,	Pick and place	To use exisiting grippers.	chainsaw_1_gripping points		Investment cost	Won't	Use as-is	Needed to be followed to use the same assembly equipment	Design engineer/ Production Engineer	Concept	In progress	

Figure 1. Expanded worksheet (Example based on C1)

5.2. Alignment with product development (PD)

An important aspect of the method of working with production requirements was collaboration between the different stakeholders. Therefore, the method needs to be aligned with the PD process. The PD process of the two case companies was studied and aligned with the general PD process (Ulrich and Eppinger, 2012). An analysis of production preparation at case companies showed that production preparation workshops conducted in C1 provides a forum for stakeholders to collaborate and discuss producibility issues. Based on this, the phases of the Lean 3P (Coletta, 2012) were used to formulate the scope of each step of the production requirement specification method. The four phases in Lean 3P are knowledge gathering, innovation, prototyping and redesign and optimisation. The alignment between the production requirements method, product development and Lean-3P is described in the subsequent text. The method to work with production requirements can be divided into the following three steps: requirement setting, requirement analysis and requirement follow-up. In the requirement setting step, the production engineer looks at the information available regarding the project and identifies, defines and structures the production requirements. The product development phases, from market input to planning, are included in this step. This is mapped to the knowledge-gathering phase of the 3P workshops as there is high uncertainty regarding the product and production. The expected outcome of this step is an experimental proof of concept with the initial product architecture and the TRL level is four; however, it can vary depending on whether the module is carryover or new, enabling a producibility assessment and the creation of a production requirements worksheet. The purpose of the production requirements in this phase is to act as guidelines to initiate discussions. The next step in the method is the requirement analysis in which collaborative decision-making happens and includes concept development, system-level and design phases of PD. The TRL matures from five to seven, and more information has been gathered regarding the product. Furthermore, the production team finalises the assembly concept, orders tooling and equipment and produces the samples for testing in this phase. Therefore, there is maturity relating to prototypes. This step is aligned with the 3P innovation phase as there are discussions between the design and production engineers regarding the requirements, prioritising them and deciding on an action plan. The next is the follow-up step that is mapped to the

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testing, refinement and production ramp-up phases of PD and prototyping and redesign and optimisation in 3P. In this step, the requirement's action plan is finalised and added to the production requirement database for future usage. Figure 2 shows this alignment.

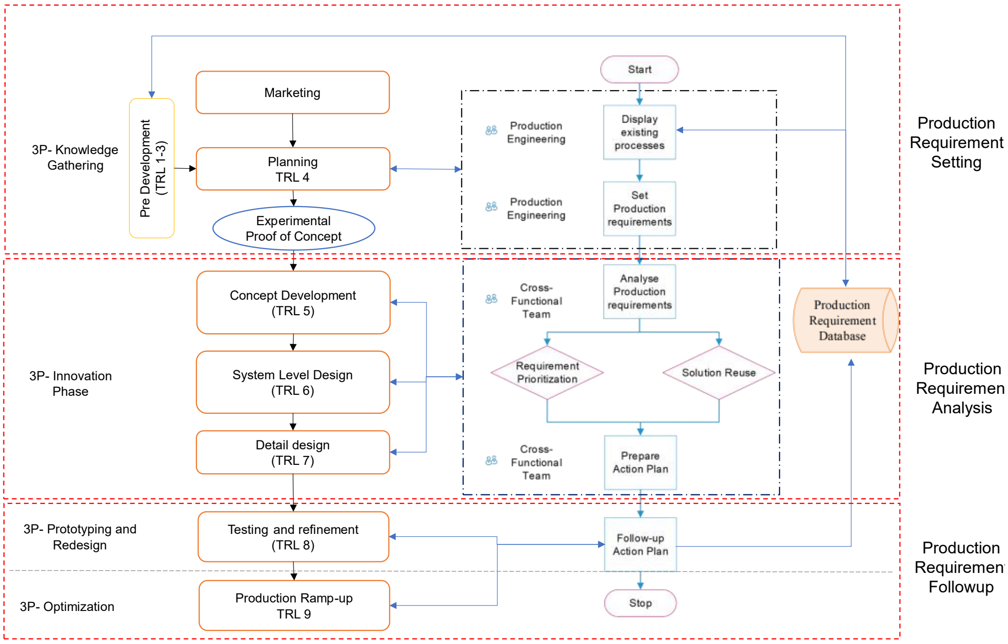

Figure 2. Alignment of the production requirements process with product development and 3P

Table 3 describes how the production requirement method can be used in the previously discussed scenarios. These scenarios vary based on the decisions made during the project start-up regarding the product and production plans, and they depend on the product and production maturities.

Table 3. Production requirements usage in different scenarios

	Scenario	Use of Production requirement
1	Existing product - existing production	Fewer changes are possible in this scenario as both the product and production systems are less flexible. The production requirements worksheet is used to check the feasibility and prepare the change assessment using the consequence information.
	Existing products - new production	The production requirement worksheet can be used to plan the production system. Existing production requirements are used as a base and the action plan can focus on the requirements that need to be improved.
2	Variant product-existing production	The production requirement can be used along with the carryover analysis to determine the requirements that act like constraints and those that act as guidelines. TRLs guide production engineers in this assessment for requirement setting.
	Variant product-new production	The production requirement worksheet can be used to plan the production system. Existing production requirements can be used as a base and the action plan can focus on the requirements that need to be improved for carryover modules. For new modules, the product and production systems can be developed together.
3	New product-existing production	The production requirements can support the R&D to reduce uncertainties by giving inputs on the best practices in production and existing requirements. The base object can be used to see how multiple product families can be supported by the same production line.
	New product-new production	The production requirements can act as a repository of best production practices and interfaces between product and production systems and are used to plan the co-development of product and production systems by making the knowledge easily and readily available.

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Figure 3 shows a potential way of accessing and using the production requirements method. The tools consolidate the information from the production requirement worksheet. The tool dashboard allows for filtering based on product type/family, variant number, module/component, project phase and process. This filtering process can be used based on application scenarios. The TRL of different modules/components are displayed accordingly, which helps to decide if the production requirement acts as a guideline or constraint. Finally, the existing production requirements are displayed with details about existing solutions, such as requirement category, requirement description, manufacturing rationale and images, which can be copied to the worksheet and reused later.

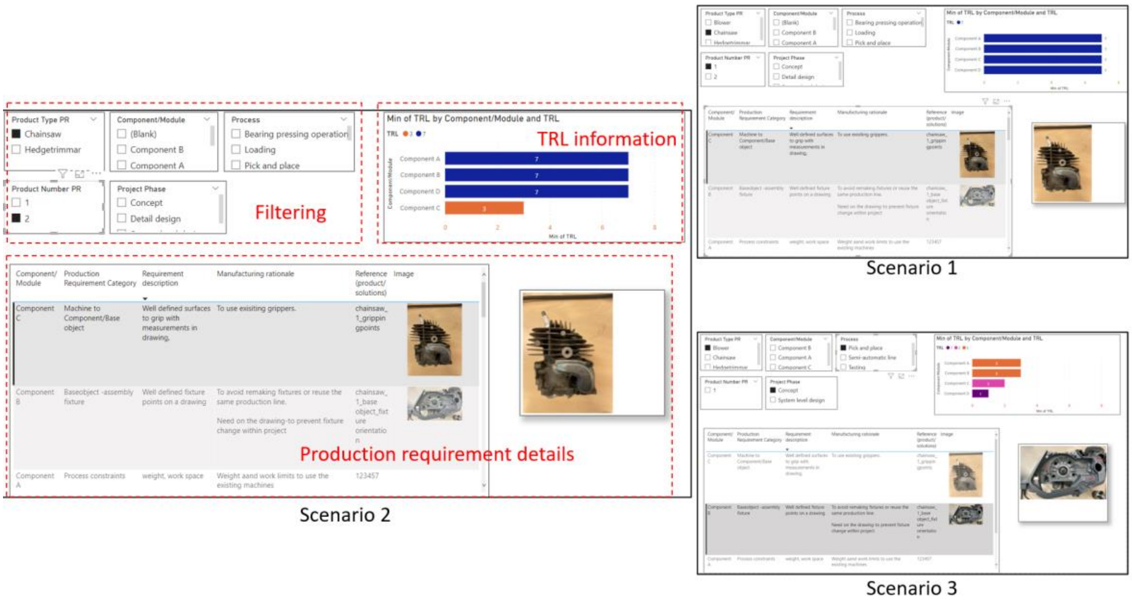

Figure 3. Demonstrator of the method (Example based on C1)

6. Analysis and discussion

Agility to changing requirements is critical for the success of a product development (PD) project and production should be capable of handling varied demand levels (Santos et al., 2017) and assets are needed to support manufacturers (Wiesner et al., 2018). Future product development can raise challenges for manufacturers such as balancing carryover or legacy systems and new systems and embracing circularity and sustainability (Isaksson and Eckert, 2020), increasing the need for flexible and reconfigurable manufacturing systems (Skärin et al., 2022). Tools are needed to provide a common language between the product and production domains to communicate their requirements (Ferreira et al., 2021). A need to align the production requirements with product and production maturities and support in the production preparation process was identified by Areth Koroth et al. (2023). This paper presented a method for working with production requirements during PD, aligning to product maturities. Interviews and document studies at the companies showed that innovation projects run separately and are introduced into the product development process when there is an experimental proof of concept. Otherwise, they worked mostly with variant development. There is an understanding of the product to initiate producibility discussions when the product enters the concept development phase. There is a lack of manufacturing resources and a lack of understanding of the maturity levels as some of the subsystems are carried over. This resulted in production involvement in end-of-concept phases when the products are matured and there is less flexibility. Due to module carryover, enough details are often available in the concept phase to start discussing producibility as the basic product architecture is set. Combining the production requirements method with technology readiness levels (TRL) will enable the development of a common understanding and use as a manufacturing knowledge source for both product and production development. Company studies, as well as articles (Ferreira et al., 2021;DOD, 2018; Ward et al., 2018), have shown the potential of using TRL to communicate the maturity of systems and sub-systems in a product development project and align with production development. Adding TRL to

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the production requirement method will give the production engineers information to perform carryover analyses during the production requirement setting. Carried-over components or systems will have higher maturity and can have more constrained production requirements. New components or sub-systems will have lower maturities. Here, production requirements can act as guidelines and are open to discussion, enabling the prioritisation of the requirements and the optimum use of production personnel for production preparation in the early phases. The production requirements method was updated to accommodate this maturity consideration. The worksheet was expanded with fields of processes and phases at which the requirements were finalised to provide support in deciding whether the requirements should be a guideline or a constraint during knowledge reuse. The workflow presented showed the alignment between the product development process, production requirements method and production preparation process. The worksheet not only acts as a knowledge source for future production requirement setting but also provides input to the pre-development teams regarding production capabilities and needs. Three scenarios were identified in which the method can be used based on whether the product is existing, variant or new and the production line is new or existing. The method used tools already existing in the companies to demonstrate its working in different scenarios, which supported the use of familiar tools for practitioners, thereby reducing the need for new knowledge to use the method, which was one of the hindrances to digitalisation highlighted by Wiesner et al. (2018). The steps in the production requirements method can be summarised as identifying focus areas, identifying requirement categories, requirement setting in the worksheet using existing production requirements and TRL information of systems and components, collaborating with stakeholders such as design engineers to prioritize production requirements and prepare an action plan and then following up and saving it for knowledge reuse. Figure 4 shows the different steps of the method.

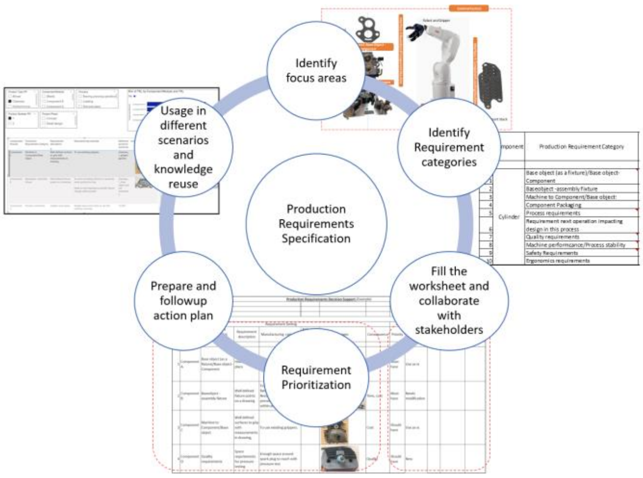

Figure 4. Steps of the method

Evaluation workshops were conducted in the case companies, involving participants who contributed to the data collection activities. The method was presented, an evaluation questionnaire was given to the participants and then the responses were recorded. The workshop results showed that the method contributes to the identification, definition and structuring of production requirements. Some variations in responses regarding traceability were observed, as Excel-based support can be difficult for version management; however, it can still improve the current way of working through a structured method of working with production requirements and improve understanding among the stakeholders. The method can be implemented in the PD process in companies but may need some modifications to align with each company's process and organisational support. C1 identified that this method can support their 3P workshops. Both companies expressed that the tool is useful during variant introduction (Scenario 2), as there is a good balance between the knowledge available and the uncertainties of change on both the product and production sides. In Scenario 1, the respondents felt that it may be difficult to motivate the resources needed to work with this method, as it depended on the scale of the project. Both companies agreed that this method can be used in Scenario 3, as it may be easier to collect data from existing equipment that can be included in the development process. Due to the lack of production

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representatives in the concept phase, this method guides the identification of critical production requirements. Challenges in implementing this method are the involvement of the right stakeholders, organisational support, effort versus benefit trade-off and educating the people involved. The results from the questionnaire are summarised in Figure 5. The evaluation workshop highlighted that although the method was useful in structuring production requirements, its applicability could be fully evaluated only through complete implementation during the product development process. The use of well-known tools increased ease of use and understanding but reduced the traceability of the requirements due to version management difficulties.

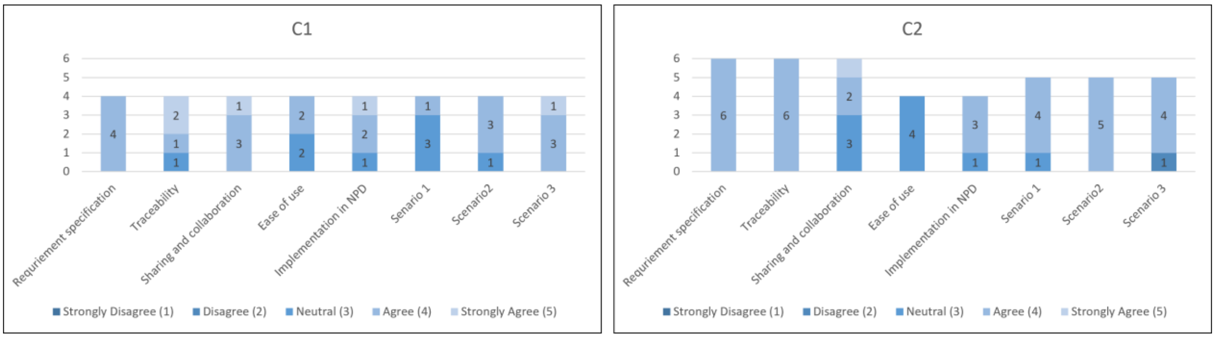

Figure 5. Summary of workshop responses

The method of working with production requirements enables the capture of production knowledge in a structured way and have a production requirement database. Future work can combine this with product platforms and assets to enable producibility assessment. The method needs to be strengthened based on requirements management. Opportunities and challenges raised by Industry 4.0, sustainability considerations and circularity towards integration between product development and production and how production requirements can be used is another interesting avenue.

7. Conclusion

Production knowledge for design engineers in the early phases is critical for reducing uncertainties and drawing on the full potential of production capabilities. In addition, collaboration between design, production and other stakeholders is important for product and production development to be able to tackle customer requirements, production capabilities and vision. The method presented in this paper achieves this by providing a structured method of production requirement specification, capturing not only the requirements but also the rationales and consequences, emphasising decision-making through collaboration. Furthermore, the method uses TRL to support production engineers in conducting component/module carryover analysis and identifying the product and production maturities aligned with the product development process to formulate the requirements and reduce ambiguities. Thus, the method supports production engineers in structuring their requirements and sharing them with design engineers, improving collaboration through a common language and a clear understanding.

Acknowledgements

The authors would like to thank the participating companies, the respondents, the IDEAL project group, the Swedish Knowledge Foundation and the SPARK environment at Jönköping University for their support.

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https://doi.org/10.1017/pds.2024.22 Published online by Cambridge University Press