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INFORMATION FLOW ANALYSIS ENABLING THE INTRODUCTION OF ADDITIVE MANUFACTURING FOR PRODUCTION TOOLS-INSIGHTS FROM AN INDUSTRIAL CASE

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ABSTRACT

Additive Manufacturing (AM) has traditionally been used for prototyping of products, however, in the last few decades, it has seen a rising growth in the manufacture of final products. The addition of AM as a manufacturing method in the portfolio of a company's production capabilities increases the complexity of decision-making. This is because the decisions are often not based on the same criteria and constraints, as related to conventional manufacturing processes. In this paper, we investigate this challenge by studying how AM affects the current workflow and the associated information flow for a design-make process in a Swedish manufacturer before and after the integration of AM. In this paper, it is argued that apart from an understanding of how to design for AM, it is equally important to consider how introducing AM alters the existing information flow and how to benefit from information available in various design-make process steps to facilitate decision making process. The result clarifies that the current process relies largely on tacit and experiences-based knowledge, whereas to take advantage of AM, more precision is required to capture and process the available information.

Keywords: Additive Manufacturing, Industialisation, Information management, Decision making

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1 INTRODUCTION

Additive Manufacturing (AM) has rapidly developed over the past 30 years, often described as offering a revolution in manufacturing with numerous attractive features, such as increased design freedom, and the opportunity to better optimise weight and strength of parts (Tian et al., 2022). AM has traditionally been used for prototyping of products, however, in the last decade, it has seen a rising growth in the manufacturing of final products as well (Thompson et al., 2016). Consequently, the addition of AM in the portfolio of a company's production capabilities has increased the complexity of decision-making in both product and process design. This is because AM design requires new ways of thinking and it is often based on different sets of requirements and constraints compared to the conventional manufacturing processes (Wang and Blache, 2017). Specifically, a company may have an established process workflow built around conventional manufacturing methods, which may hinder reaping all the benefits which AM has to offer. Moreover, designers often rely heavily on tacit knowledge, making adaptation of a new technology difficult. This makes it challenging to integrate AM into existing information flows understanding which can be instrumental in various consequential aspects. For instance, AM can have significant impact on supply chain management processes, components (Oettmeier and Hofmann, 2016) and overall business strategies (Rylands et al., 2016). Further, in order to utilize the full potential of AM, the importance of following design for AM (DfAM) guidelines is also well recognized (Thompson et al., 2016).

While the importance of information flow analysis and knowledge on DfAM are clear, there is a gap in the understanding of how such analyses of the information flow can both influence and benefit the design process. For instance, while many researchers have put effort on optimising design for AM, it is usually done in isolation, not considering the position of AM in the value chain and its consequential interaction with the associated design processes. Further, researchers agree that AM requires a fundamentally different way of thinking about design than when conventional methods are used to manufacture a product. Therefore, there is a need to study how the introduction of AM in a company, where traditional and often pre-existing manufacturing processes exist, influence the overall information flow in realisation of a product. It is further important to systematically analyse the information throughout the process, which potentially influences the design decisions. In this paper, we therefore investigate a case of how introduction of AM is affecting the current manufacturing information flow in a Swedish Original Equipment Manufacturer (OEM), including its utility in the design process. The case focuses on design and manufacturing of simple production tools often used as aids in the production line. The following research question is addressed in this paper:

RQ1: In what way the design process of production tools is impacted when introducing additive manufacturing?

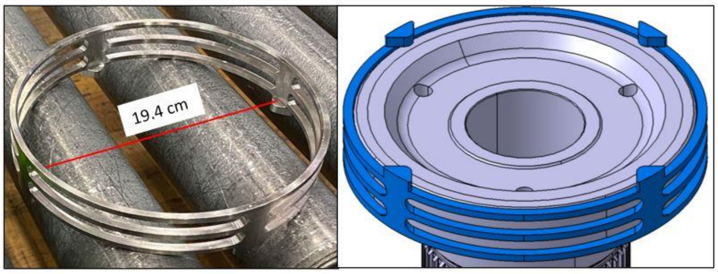
The remainder of the paper is structured as follows; in the next section a description of the methodology used to investigate the research question is discussed followed by Section 3, a summary of the related reviewed literature. Next, Section 4, presents the observations from the case study. In Section 5, results obtained from the study are analysed and discussed, followed by the conclusions and future research recommendations in Section 6.

2 METHODOLOGY

This study is in line with the recommended second step of Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009). In the terminology of DRM, the second step called Descriptive Study 1, aims to increase the understanding of the current situation and how to respectively position the research problem to that. More specifically, a comprehensive descriptive study 1 was performed comprising an empirical study as well as a literature review. To accomplish this objective, the study focuses on clarifying the workflow along with its accompanying information flow in a typical industrial product design and manufacturing process. The workflow is analysed before and after the introduction of AM to investigate how this change affects the design decisions. The study involves a global, well-established manufacturer of construction equipment. In the following subsections, Section 2.1 gives a brief introduction of the industrial use case and Section 2.2 explains the details of the methodology used.

2.1 Industrial use case

The use case under investigation was the introduction of AM for production tool manufacturing in one of the large Swedish OEMs. Figure 1 shows one such production tool which is used to protect gears during the washing process. At present, the tools are manufactured using a combination of conventional techniques such as welding and machining, produced in metal or polymer. Such tools are designed and manufactured for unique applications in the production line and are therefore produced in low volume. The design and manufacturing of such tools are seemingly straightforward and the engineering effort per tool (or per design) is limited when compared to other high volume production parts as is the case for their components and assembled products for the end customers. These characteristics make AM a suitable candidate for manufacturing of such tools for the use in the production process. Although the tools in question are currently made in polymer or plastic, the study was limited to Fused Deposition Modelling (FDM) polymer printing as the metal AM would be overqualified to be deployed for such simple case.



(a) *(b)*

Figure 1. Gear protector a) The physical part manufactured by milling b) The CAD model of the same tool, showing how it surrounds the gear

2.2 Information flow analysis methodology

The following briefly discusses the steps undertaken to answer the research question raised in Section 1. Additionally, Table 1 provides the overview of the activities undertaken.

a) Investigation of the pre-existing tool design and manufacturing process (the "as is" process)

As highlighted in Section 1, there is a need to study how AM affects the information flow of the current manufacturing process. To investigate this, several semi-structured interviews and workshops were carried out to understand the "as is" workflow. The main participants in these interviews were the design engineers, the manufacturing engineers, the end users of the product and an innovation manager involved in this project. A total of eight semi-structured interviews and workshops were held on the company site and three interviews were held online. To specify the scope of the investigation, the starting point of this workflow was considered as the point when the tool is ordered by the internal customer and the end point to be when it is manufactured and delivered. The workshops were held both online and on-site at the factory.

b) Identification of the necessary steps to introduce AM to the current tool design and manufacturing process (the "to be" process)

To study how the introduction of AM will influence the current workflow, first, the necessary steps for a generic AM design and manufacturing process(es) was outlined. This was carried out primarily based on the guidance available in the literature such as in Diegel et al. (2019). Second, to investigate this in practice, three tools currently used by the OEM in the production line were chosen to be redesigned and manufactured by AM. This process was initiated by gathering information about the available, previously manufactured tools and how they fulfil the customer's need. This was done during multiple factory visits covered by four semi-structured interviews with design engineers, manufacturing engineers and the end users. As the next step, the parts were redesigned for AM with the aim to improve various facets of the design. DfAM guidelines including Topology Optimisation (TO) were also considered. The redesigned parts were then printed and evaluated in practice in the assembly line by the end users. Feedback was gathered by interviewing the end users in three semi-structured interviews on the factory site. Some tools needed design improvements, therefore were redesigned, and tested again. Finally, the steps observed in the design-to-manufacture process were mapped out and integrated with the previously explored pre-existing design and manufacturing process as explained in point (a) above. A modified IDEF0 model (Presley and Liles, 1995) was used to visually demonstrate the "as is" and "to be" processes. To be concise, we have only described one of the three case examples in this paper.

c) Analysis of the information flow of the processes using typical production tools
Various steps of the design and manufacturing concerning the selected production tools were analysed, both before and after the introduction of AM. The aim was to get a better understanding of the differences in required criteria and offerings for each manufacturing technique enabling a more comprehensive trade-off and design decisions.

Table 1. Overview of the methodology taken to explore the research question

Activities in sequence	Description
"As is" process investigation	The investigation of the pre-existing tool design and manufacturing process ("as is" process)
"To be" process investigation	Identification of the necessary steps when introducing AM to the current tool design and manufacturing process ("to be" process)
Data flow analysis	The analysis of the information flow of the processes using typical production tools

3 LITERATURE REVIEW

A number of studies have been devoted to exploring how to design for AM. For example, Diegel et al. (2019) book provides a set of guides to designers on how to design for AM, for both polymer and metallic products. Furthermore, there has been growing interest in understanding how AM would affect the traditional design process. As an example, Mellor et. al. (2014) argue that a product design will significantly change, as the traditional manufacturing constraints are loosened and replaced by the constraints particular to AM. This was also investigated by Borgue et al. (2019) who presented a model-based method for redesigning products for AM by replacing traditional manufacturing constraints by AM constraints. The design engineers therefore need to learn new skills such as to know how and when to design for AM.

While implementation of AM requires designers to rethink the process and approach to design, it is equally important to investigate beyond technical aspects and consider how introducing AM alters the existing workflow. Birtchnell and Urry (2016), for instance, view AM as a disruptive technology and argue that the traditional information flow of the manufacturing system must be redesigned to gain maximum utility of the technology. In another work, Rylands et al. (2016) demonstrate how adoption of AM influences the information and material flow, and suggest that "co-existence" of traditional and additive manufacturing, strengthens a company's capabilities, bringing economic benefits and helping the business grow. Belkadi et al. (2018) report from companies introducing AM for component design and highlight the need for understanding the limitations and complying with existing digital infrastructure.

Panfili (2019) states that "*The backbone to the industrialisation of additive manufacturing is digitalisation*". Digital solutions drive and control the whole process chain from design to post-processing. Design solutions and CAD software ideally need to integrate with Product Lifecycle Management (PLM) tools in addition to the AM machines and other interfaces. Research also highlights several opportunities to improve AM digital infrastructure (Kim et al., 2015). For example, Mies et al. (2016) investigate the application of digital threads for AM and argue that data related to AM material, process parameters, tests and more can be captured throughout the lifecycle of a product. This, in addition to improving efficiency and innovation, will help in bringing opportunities to decrease cost and lead time. In another study, Bonham et al. (2020) study how digital threads can be designed and utilised for additive manufacturing of a kayak. In the aforementioned studies, researchers highlight the importance and affectability of digital information flow mapping of AM to facilitate the democratization of the technology not focusing on how this information would affect the design procedure.

In the studies mentioned above, researchers explored the process of designing for AM, its potential impacts on existing workflows and the importance of digital infrastructure in the implementation of AM. However, the review reveals that not much attention has been given to how information flow analysis could influence the design process. This arguably, has significant implications on design advancements and the selection process of suitable manufacturing process for a product. In a previous work related to the project this paper reports on, Mallalieu et al. (2022) carried out a more thorough systematic literature review on digital infrastructure considerations in currently available DfAM methods and concluded that there is a general lack of attention towards the digital infrastructure aspects of AM. The authors therefore recommended further studies on the topic. The following case study aims to further address that by investigating what elements are available in the design and manufacturing information flow that potentially influence the design decisions.

4 CASE STUDY OBSERVATIONS

Based on the procedure described in the methodology section, the following observations were made:

4.1 "As is" production tool design- and manufacture- process investigation

The process flow shown in the top of Figure 2 (in blue background) represents the steps currently followed for the production tool order-to-delivery workflow. When the end user (operator) requests a tool, depending on whether the tool is a new design or not, the tool order process takes different routes. If the design is already available and no adjustments are needed, it is directly sent to the manufacturing department. However, if the design is new or is to be an improved version of an older design, the order is sent to the design department instead. In the design department, the urgency of the order is evaluated first and a corresponding priority value is set, relative to the other orders in the queue. If the tool has priority, the design engineer checks the requirements and if needed, asks the end user for additional information. When sufficient information about the tool is captured, the design process progresses forward. At this step, the CAD files, drawings, and other important information about the tools are documented. After this, the drawings and information related to manufacturing are

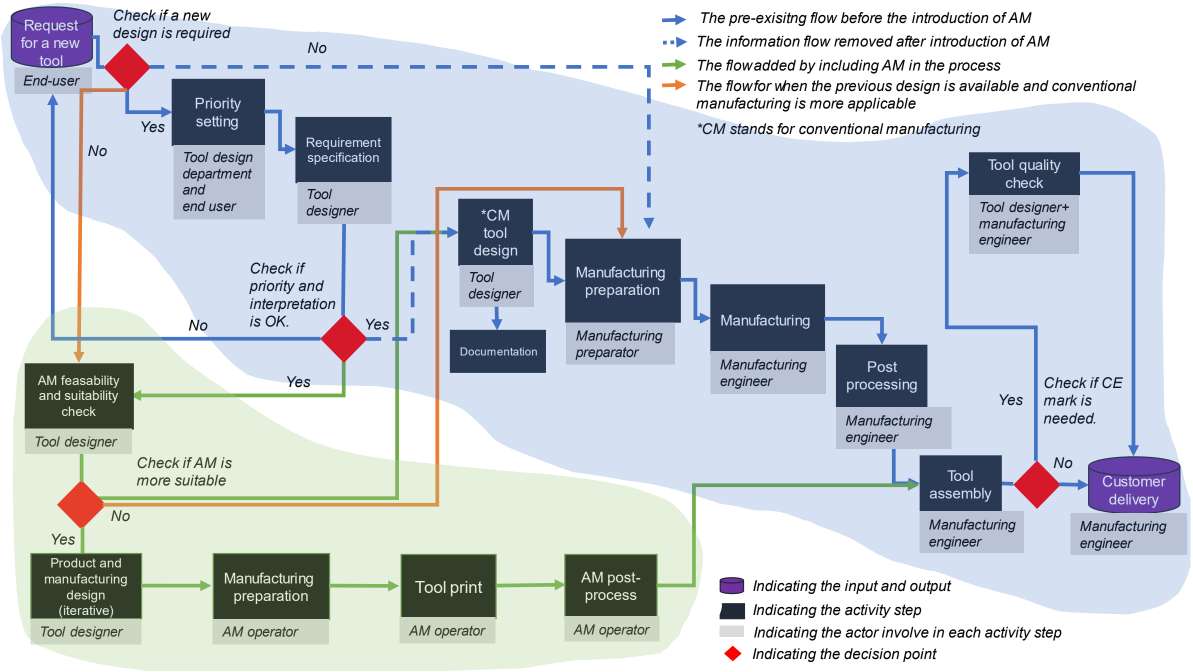


Figure 2. Critical activities for production tool design and manufacturing before introducing AM to the workflow (on top, in blue background) and additional activity steps after introducing (at the bottom, in green background)

handed over to the manufacturing engineer. Then, the manufacturing engineer checks whether the tool/parts of the tool needs to be manufactured in-house or through an external supplier based on the available capabilities and cost. If it is to be made in-house, they check the availability of the required machine and other related equipment. The tool is then manufactured and if needed, assembled. Some of the tools may also need to have a CE marking (conformité européenne), which means they are deemed to meet EU safety, health and environmental protection requirements (Ballor, 2022). In such a case, the tool undergoes relevant tests before being delivered, otherwise it is delivered directly to the customer (the end user). Post processing is not considered as the main step of the workflow as the studied tools were fairly simple. This step is added manually as it is considered as one of the main activity steps in the manufacturing process.

The current tool design and manufacturing process is a well-established work routine in the case company, relying on the skills and collaboration between the actors involved. Since the total work effort is relatively limited, and the products (tools) are designed internally, there has not been a need to use the full PLM environment, which is used primarily for the end product development in the company. As such, the company's PLM system is primarily used to handle more complex products. As the next step, it is of interest to investigate how AM may influence the currently established process ("as is").

4.2 "To be" process investigation (Introducing AM to the workflow)

The process flow illustrated in the bottom of Figure 2 (in green background), represents the additional activities which must be conducted if AM is introduced in the workflow. The recommended process starts when the end user orders a tool. Depending on whether the tool needs a new design or not, the flow takes different routes. If a new design is needed, it will take the same path as before, i.e., it will be sent to the design department where priority and requirements will be checked. Thereafter, introduction of a new step is suggested where the design engineer evaluates whether AM can be feasible and can add more value than the current manufacturing technique. This evaluation is based on criteria such as lead time, cost, material, new design features offered by AM, etc. If AM is not feasible or does not add a major value, the process will be forwarded to the traditional manufacturing preparation stage and will take the previous path as illustrated by blue arrows in Figure 3. Whereas, if AM offers more value to this case, detailed design of the part is carried out considering DfAM guidelines. The designed part is then iterated between the design engineer and the end user until it is satisfactory. This is followed by manufacturing preparations such as setting up the accuracy of the print and the build orientation adjustments, followed by the printing process. At the end, post processing including cleaning and support removal (if applicable) is performed.

However, if there is no need for a new design, instead of taking the previous route, i.e., sending the part directly to the manufacturing department, the route depicted by the orange arrow in Figure 3 is taken. At this point, the applicability of AM is assessed. If AM suits the application better, the path related to the AM process will be followed, otherwise the process proceeds through the conventional flow (shown by the arrows in blue).

4.3 Information flow analysis using three sample production tools

Based on the investigated production tools, the critical design information needed from each activity step is outlined in Figure 3. Having access to this information during the design step, helps the designer to make more comprehensive design decisions. In the current design process, the design department has three major responsibilities:

- Setting the priority for the products to be designed
- Specifying the product’s requirements
- Designing the product

However, with introduction of AM, an additional step (before starting the design process) is added to their responsibilities, referred to as “AM feasibility and suitability check” in Figure 2. In this step the designer needs to decide either to design for AM or design for the traditional manufacturing process. Additionally, the designer can check if unique characteristics of AM can be useful or not, for instance, whether a customized design or topology optimised design is of interest or not. Additionally, they can compare design and manufacturing time and cost for traditional and additive manufacturing. Some of these examples are illustrated in Figure 3. This added new activity step requires gathering information from different activity steps such as product requirements or manufacturing constraints. These are required in order to make a more comprehensive design decision.

A case study example is used to elaborate this further. Figure 4 (a) shows one of the investigated tools. As previously discussed in Section 2, this tool surrounds a gear, protecting it against impact marks during transportation in a washing machine basket. The design must not only enable a robust support to the gear but also must not obstruct the washing process. Figure 4 (b) shows the tool redesigned for AM. This design or similar (including perforations in the body) reduces material consumption and at the same time improves the washability of the part while also keeping the gear safe from impacts, scruffs, and scratch marks. In this case, the requirements allowed switching material from steel to polymer which also helped in reducing weight and creating a more ergonomic design. This is one of the examples in which AM adds more value compared to the conventional manufacturing technique.

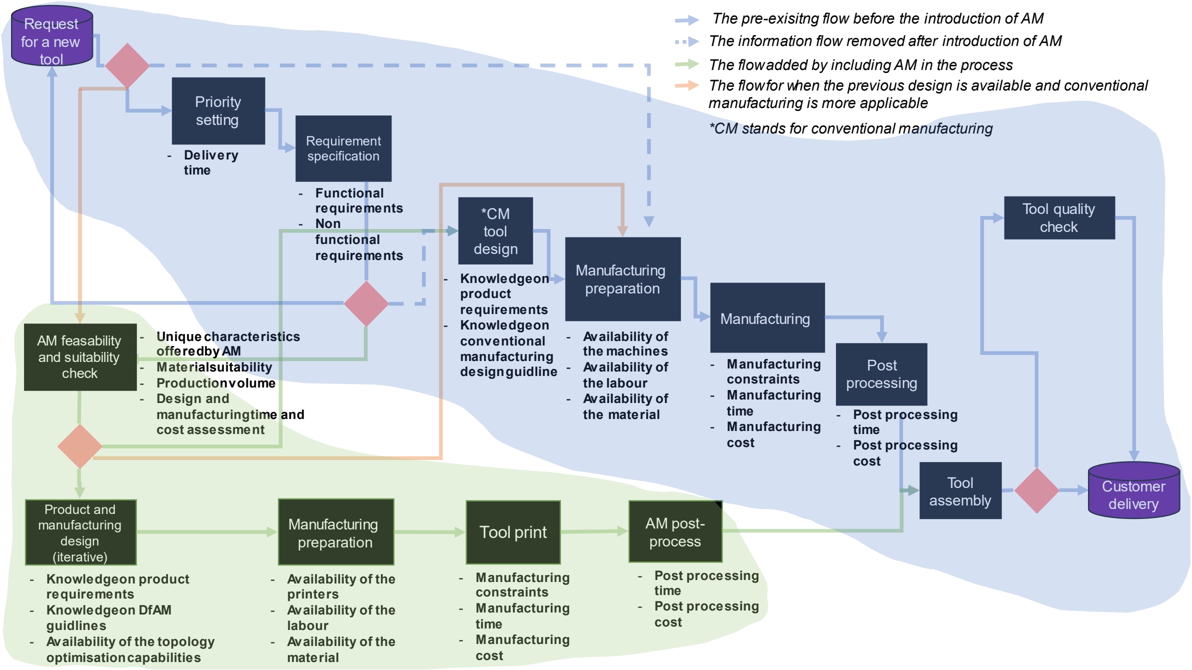


Figure 3. Summary of some of the important criteria necessary for each activity step, affecting design decisions.

Table 2 shows the quantified results in terms of lead time, material cost and total weight of the tool. Data for the conventional manufacturing method was extracted from the latest order of the same tool. 17 such tools were ordered and manufactured, which comprised of two weeks "on hold" in the production queue. The time dedicated to design the tool for both the conventional and the AM processes was observed and found to be similar, at approximately eight hours. When it came to manufacturing lead time, however, a reduction of six times was observed when using AM, compared to the subtractive manufacturing. Material cost was also slightly lower in the case of AM. However, these are only some examples highlighting the information needed to decide between different manufacturing techniques. It is vital to consider other aspects such as the batch size in the evaluation. If the batch size is high a limitation of printers in-house may make AM an unsuitable alternative. As another example, the application of AM provides more design freedom and therefore might help to cover more of the requirements of the product. At the same time, it must be investigated if the material characteristics required for the part is achievable and the corresponding material printable. If yes, whether such a capability is available in-house or not. As another concern, changing the design or material may come with a risk of uncertainty. In the case of the gear protector, the material was changed from metal to polymer. This part needs to be resistance to temperature around and above 50 ℃ as required for the washing process. An important question arises regarding the durability of the new polymer at such high temperatures, and whether prolonged exposure could potentially lead to health concerns for operators, given the possibility of odour emissions. In this case, it is recommended to add a new block to the "to-be" process, indicating the possible testing procedure needed to conduct due to the imposed changes. This is not shown in the Figures 2 to decrease complexity.

To summarise, in order to reach a more holistic understanding of different manufacturing processes' offerings and limitations, information/criteria need to be gathered from different activity steps. An overall view of the required activities for both AM and conventional processes facilitate the trade-off between the manufacturing process capabilities.

(a) *(b)*

Figure 4. Gear protector tool: a) The physical part manufactured by milling, b) The redesigned tool manufactured with AM

Table 2. Comparison of AM and traditional manufacturing process for gear protector tool

	Design and Manufacturing lead time (h)	Material cost (SEK)	Weight (g)	Material type
AM (Fused Deposition Modelling)	16	1050	136	ASA
Subtractive Manufacturing (Milling)	93	1300	3580	Stainless steel

5 DISCUSSION

To validate the utility of the method discussed in this paper, follow-up discussions with engineers at the company who were engaged in the process was undertaken. According to their feedback, the process helped them to identify the differences, advantages, and disadvantages when considering AM in the workflow. This indicates that the proposed process was relevant and useful for the stakeholders in the process. Mapping out information and activity flow for the established design-to-manufacturing process before introducing AM and after, provides valuable insights on the process itself, its limitations, and its offerings. The insights can be summarised as follows:

Formal collection of tacit/explicit information: The production tool design process relies heavily on experienced engineers working together and sharing information (in an iterative process) when needed. Formally capturing such process by necessity, represents a somewhat idealised description of the case. Further, the complexity of capturing the otherwise tacit experiences and rationales means that the workflow representation can be complex even for simpler products like the tools discussed in this paper. While the direct involvement of these engineers in the process ensures sufficient validity, a lot of useful information may not be captured formally and maybe lost in the currently followed process. Therefore, to benefit from the capabilities of AM, more information and data need to be formally captured and analysed. This was also highlighted by Page et al. (2019).

Relevant information collection: To implement AM, it is vital to capture both the functional and non-functional requirements of the product. For instance, beyond the functional requirements, a tool may be required to have certain durability, strength, etc. Capturing this information further facilitates the material selection process and traceability. Furthermore, there may be process related constraints which influence the final design. For example, the printer may have certain limitation on the build volume, direction of print etc. Collecting this information is therefore vital in the workflow. However, not all the collected information may be useful to make a trade-off between AM and the established manufacturing process. For instance, requirements such as part elasticity may restrict some manufacturing methods such as casting from being deployed. In such a case, information relevant to the discarded process becomes unnecessary.

Need for a decision support tool: A need for a systematic way of capturing critical criteria was highlighted by the designers. While the mapping of the process may help in the trade-off studies, the procedure may be cumbersome for application on every instance of the tools produced. Therefore, a simplified tool for design engineers and managers which facilitates such trade-offs in a factory-production setting may be of utility. This systematic comparison becomes more critical when the criteria change, or new criteria is required for the product. For instance, manufacturing of a more environmentally sustainable product is becoming more crucial compared to before. This highlights the need for a tool which can systematically capture required information and facilitates the comparison between available manufacturing technologies from such points of views.

AM sustainability aspect: AM as a manufacturing technique offer several advantages for sustainable product development. Some studies have shown the technology to be a more environmentally sustainable solution, as it enables extended product life, less wasted materials and a shorter supply chain (Ford and Despeisse, 2016). In the case study considered in this paper, AM reduced the material consumption, added extra features without an increase in cost or extra tooling and also decreased the manufacturing time. Therefore, this technique offers opportunities for more circular solutions. However, there are many aspects that were not considered in this study, including social and environmental life cycle analysis.

Need to account for uncertainty: Introducing a new technology to the current workflow, increases the uncertainty level of the system. Currently, the engineers are used to the traditional process and most of the information they rely on, are based on the currently available technologies. However, introducing AM, might require change in design, material, or both. For instance, in the case study presented in this paper, some parts were traditionally manufactured by metal, however, AM provides the possibility of using polymers. This can directly decrease the material consumption, manufacturing cost and time, although it also comes with a higher level of uncertainty, e.g., the longevity of the new product or its safety is unknown without rigorous testing. This needs to be considered and if needed, new test procedures need to be defined.

PLM application: To have a better record of the information and the possibility to reuse data to improve the design process, implementing a PLM system was identified as one strategy forward. Using a PLM system would provide the capacity to manage a richer set of data along the process. The PLM systems available in companies, however, may be designed primarily for their end products and may not be tailored for the manufacturing aids such as the tools considered in this paper. Further, the end products generally have several orders of magnitude more complex information flows than the tools discussed. This further raises the question about the potential trade-offs between the cost and effort required to use such sophisticated PLM systems, especially for relatively simpler, internal, and agile processes such as production tool design.

6 CONCLUSION

This paper intended to clarify the similarities and differences in design and manufacturing process of production tools before and after introduction of AM, in an OEM where a pre-existing manufacturing set-up exists. The study showed that introducing AM for production tools, impacts both the design and the general process workflow. It can be concluded that to make a comprehensive design decision, it is vital that information is captured from different activity steps. Introducing AM as a new technology, requires systematic capture of tacit/implicit information. Further, this change to the system demands capturing additional information previously not required. The captured information facilitates a more thorough trade-off analysis between traditional manufacturing processes and AM. This comparison becomes more crucial when the product requirements change, as in the case of manufacturing more environmentally sustainable products which has recently attracted significant attention. The challenge is to use AM when it fits best. It is therefore recommended to develop a method for facilitating such trade-off analyses between various manufacturing techniques available by collecting information from different steps of such workflows. However, workflows which at present rely on smooth and agile work practices, must also carefully consider digital supports such that they do not over administer the process thereby curtailing innovation but rather offer practical and useful decision support.

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REFERENCES

Ballor, G. (2022), "CE Marking, Business, and European Market Integration", *Business History Review*, Vol. 96 No. 1, pp. 77–108, https://dx.doi.org/10.1017/S0007680521000696.

Belkadi, F., Vidal, L.M., Bernard, A., Pei, E. and Sanfilippo, E.M. (2018), "Towards an Unified Additive Manufacturing Product-Process Model for Digital Chain Management Purpose", *Procedia CIRP*, Elsevier B.V., Vol. 70, pp. 428–433, https://dx.doi.org/10.1016/j.procir.2018.03.146.

Birtchnell, T. and Urry, J. (2016), *A New Industrial Future? 3D Printing and the Reconfiguring of Production, Distribution, and Consumption*, Routledge, London.

Blessing, L.T.M. and Chakrabarti, A. (2009), *DRM, a Design Research Methodology*, Springer London

Bonham, E., McMaster, K., Thomson, E., Panarotto, M., Müller, J.R., Isaksson, O. and Johansson, E. (2020), "Designing and integrating a digital thread system for customized additive manufacturing in multi-partner kayak production", *Systems*, Vol. 8 No. 4, pp. 1–17, https://dx.doi.org/10.3390/systems8040043.

Borgue, O., Müller, J., Leicht, A., Panarotto, M. and Isaksson, O. (2019), "Constraint Replacement-Based Design for Additive Manufacturing of Satellite Components : Ensuring Design Manufacturability through Tailored Test Artefacts", *Aerospace*, https://dx.doi.org/10.3390/aerospace6110124.

Diegel, O., Nordin, A. and Motte, D. (2019), *A Practical Guide to Design for Additive Manufacturing*, Springer Singapore.

Ford, S. and Despeisse, M. (2016), "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges", *Journal of Cleaner Production*, Vol. 137, pp. 1573–1587, https://dx.doi.org/10.1016/j.jclepro.2016.04.150.

Kim, D.B., Witherell, P., Lipman, R. and Feng, S.C. (2015), "Streamlining the additive manufacturing digital spectrum : A systems approach ", *Additive Manufacturing*, Elsevier B.V., Vol. 5, pp. 20–30.

Mallalieu, A., Hajali, T., Isaksson, O. and Panarotto, M. (2022), "The Role of Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing", *Proceedings of the Design Society*, Vol. 2, pp. 1401–1410, https://dx.doi.org/10.1017/pds.2022.142.

Mellor, S., Hao, L. and Zhang, D. (2014), "Additive manufacturing : A framework for implementation", *Production Economics*, Vol. 149, pp. 194–201, https://dx.doi.org/10.1016/j.ijpe.2013.07.008.

Mies, D., Marsden, W. and Warde, S. (2016), "Overview of Additive Manufacturing Informatics: 'A Digital Thread'", *Integrating Materials and Manufacturing Innovation*, Vol. 5 No. 1, pp. 114–142, https://dx.doi.org/10.1186/s40192-016-0050-7.

Oettmeier, K. and Hofmann, E. (2016), "Impact of additive manufacturing technology adoption on supply chain management processes and components", *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 944–968, https://dx.doi.org/10.1108/JMTM-12-2015-0113.

Page, T.D., Yang, S. and Zhao, Y.F. (2019), "Automated candidate detection for additive manufacturing: A framework proposal", *Proceedings of the International Conference on Engineering Design, ICED*, Vol. 2019-Augus No. August, pp. 679–688, https://dx.doi.org/10.1017/dsi.2019.72.

Panfili, G. (2019), "Industrialisation and Field Experience of Gas Turbine Components Made By Additive Manufacturing", *Gas Turbines for Energy Network Symposium*, No. October.

Presley, A. and Liles, D.H. (1995), "Use of IDEF0 for the design and specification of methodologies", I*ndustrial Engineering Research - Conference Proceedings*, No. October 1998, pp. 442–448.

Rylands, B., Böhme, T., Gorkin III, R., Fan, J. and Birtchnell, T. (2016), "The adoption process and impact of additive manufacturing on manufacturing systems", *Journal of Manufacturing Technology Management*, Vol. 27 No. 7, pp. 969–989, https://dx.doi.org/10.1108/JMTM-12-2015-0117

Thompson, M.K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R.I., Gibson, I., Bernard, A., et al. (2016), "Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints", *CIRP Annals - Manufacturing Technology*, Vol. 65 No. 2, pp. 737–760, https://dx.doi.org/10.1016/j.cirp.2016.05.004.

Tian, X., Wu, L., Gu, D., Yuan, S., Zhao, Y., Li, X., Ouyang, L., et al. (2022), "Roadmap for Additive Manufacturing: Toward Intellectualization and Industrialization", *Chinese Journal of Mechanical Engineering: Additive Manufacturing Frontiers*, Elsevier Ltd, Vol. 1 No. 1, p. 100014, https://dx.doi.org/10.1016/j.cjmeam.2022.100014.

Wang, Y. and Blache, R. (2017), "Selection of additive manufacturing processes", *Rapid Prototyping Journal*, Vol. 2 No. June 2016, pp. 434–447, https://dx.doi.org/10.1108/RPJ-09-2015-0123.