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The Importance of Digitalisation in Industrialising Additive Manufacturing: Learnings from the DIDAM P2030 Project

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Abstract. Additive manufacturing, a technology that has evolved significantly over the last few decades, has shifted from prototyping to final product manufacturing. Despite its potential in design flexibility and customisation, its implementation in industrial ecosystems often faces challenges, especially in companies with established traditional manufacturing methods. This paper explores additive manufacturing beyond the printing process, drawing insights from the DIDAM project in Swedish manufacturing companies. It maps the advantages of additive manufacturing to external factors influencing its success such as digital infrastructure. This mapping yields "risk factors" for its implementation. These factors are based on empirical observations from the DIDAM project to identify potential failure modes, assess risks, and provide a snapshot view of critical issues. This objective evaluation aims to support managers in evaluating the risks associated with additive manufacturing's integration into a company's manufacturing ecosystem, based on empirical findings in industrial cases as reported in the DIDAM Digital Model Guide (Digital Model Guide, 2023).

Keywords. Digitalisation, Additive Manufacturing, Design for Additive Manufacturing, Risk Analysis

1. Introduction

Additive Manufacturing (AM) as a technology has undergone intense research and development as a materials and manufacturing technology over the last decades [1]. With the maturity of the technology, its use has moved significantly from prototyping to man-

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ufacturing of final products [2]. While much of the research has concentrated on the technology itself, not a lot has been done to review its position in the overall product and process cycles [3,4]. Previous studies have shown that while companies understand the opportunities additive manufacturing has to offer in terms of design flexibility, complexity, and customisation, they often struggle with its implementation [5,4]. A core area of difficulty arises from the digital aspects of implementing additive manufacturing which often inhibits its full integration in the industrial eco-system [3]. Further, often the difficulty is exacerbated when additive manufacturing is introduced in a company where a well-established portfolio of traditional manufacturing methods exists [6].

This paper, therefore, looks primarily at the aspects of additive manufacturing beyond the technical process of printing and reports on learnings from the DIDAM project with digital value chain analyses of AM in several Swedish manufacturing companies. Firstly, we compare the advantages additive manufacturing has to offer and map them to exogenous factors influencing its successful implementation. This mapping of factors leads to a set of 'success criteria' that indicate what may be necessary for a successful implementation of additive manufacturing in a company. Finally, we discuss these success criteria against the observations made in a long-running project to validate them and assess the potential failure modes.

2. Background

Design for Additive Manufacturing (DfAM) has been a well-studied field which aims to generate guidelines on how to design for AM while reaping maximum benefits the technology has to offer [7]. Key advantages repeatedly referenced are the differences in design constraints associated with AM, as compared to products which are conventionally manufactured [8]. However, transformation of conventional manufacturing led-constraints to constraints more suitable for additive manufacturing can be a challenging task [9]. The challenges may arise from high cost of testing and certification, low confidence in novel designs and so on [9]. Further, there are significant challenges regarding design workflow. While the design freedom AM brings is a boon for designers, it also leads to a complete rethink of a product which would have otherwise been manufactured using conventional means [10], which further leads to a disruptive change in its design process. [11] for instance, suggest for a complete redesign of traditional information flows within manufacturing systems to maximise AM's potential. In contrast, [12]'s studies on two companies showed how introduction of AM may create additional value streams thereby strengthening a company's manufacturing portfolio rather than disrupting or replacing it. While there may be an argument for diversity of manufacturing capability, it may be argued that the company may have to deal with two different process and information flow leading to inefficiencies.

Further, to support the changes needed to implement AM in a company, especially to its design and production process, a significant effort is often needed on digitalisation. As compared to conventional manufacturing processes, AM more often then not may have different value chains [13], interoperability requirements [14], standards [9] and so on. Since AM is practically completely driven by a digital infrastructure, integrating it

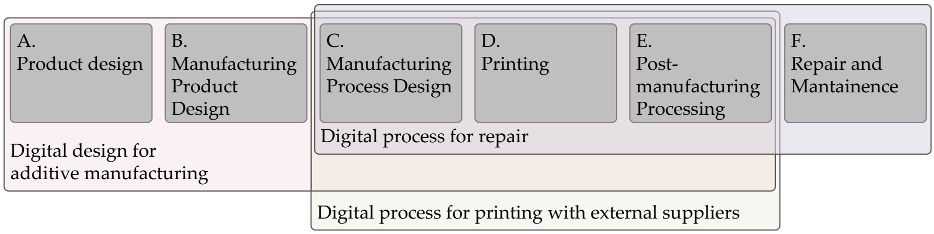

Figure 1. The generic AM workflow and the demonstrator cases coverage mapped onto it.

into existing digital infrastructure in a company, is therefore always a challenge. [15], for instance points out to the often completely digital workflows of AM-led product development, where design is carried out in CAD, which may interact with Product Lifecycle Management (PLM) software, which may interface directly with printers of various kinds. Further, companies may involve digital twins in the production workflows, driven by various motives of monitoring, predictive maintenance and process and quality control [16]. Digital solutions play a pivotal role in governing the entire process chain from design to post-processing, necessitating seamless integration with PLM tools and interfaces, in addition to AM machines and Computer Aided Design (CAD) software. Research in this domain identifies opportunities to enhance AM's digital infrastructure, with implications for efficiency, innovation, cost reduction, and lead time improvement [17,18,19]. In a more extensive literature survey from the DIDAM project on which this paper reports from, [3] revealed an overall lack of emphasis on digital infrastructure in existing DfAM methods. The gap underscores the need for further research in this area and development of broader guidelines in AM implementation. The significant lack of implementation support available to companies, especially small and medium-sized enterprises (SMEs), often leads to struggle with assessing the risks and opportunities involved with AM.

3. Case studies

The case studies are reported from a 3 year long collaborative research project in Sweden, where some of the aforementioned challenges were studied in depth. The paper presents two cases from different industries and highlights the contextual challenges which are then extracted as generalised insights.

Figure 1 presents a six step generic AM workflow, which starts from product design (marked in box A) and ends with repair and maintenance, as marked in box F. The overall objective of the project was to focus on the value chain pertaining to the introduction of AM in various industrial settings and identify the consequent needs, specifically related to the digital aspects. The project involved "Test Beds", aiming to study and implement such value chains thereby advancing the industrial adoption of AM. The three test bed demonstrators were chosen aiming a) coverage of the entire generic AM process and b) coverage of internal and external aspects of a supply chain such as external print houses, traceability, etc. The three demonstrators are mapped onto the generic AM process, as shown in Figure 1.

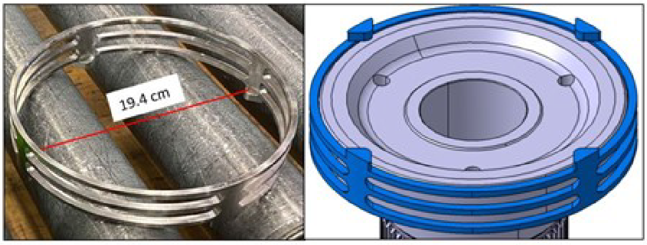

Figure 2. Gear protector (left) The physical part manufactured by milling (right) The CAD model of the same tool, showing how it surrounds the gear [6].

3.1. Case 1: Digital design for additive manufacturing

The primary aim of this project was to demonstrate the value of digital design for AM and the identification of AM adapted tool design procedures. The demonstrator use case involved the introduction of AM as a method to manufacture tools used in the production line of a large scale Swedish Original Equipment Manufacturer (OEM). The tools in question are used for special and unique applications in the production line and are therefore manufactured in very low quantities. For example, Figure 2 shows a milled gear protector which is used to protect a gear during a washing operation. For the OEM such tools are characterised to require low design time and effort, in contrast with components for end users which generally require much more design time and effort, and are produced in much higher volumes.

3.1.1. Case 1: Study method

The study method comprised of a combination of a series of interviews, workshops and observational studies. The studies were primarily conducted in the "low-volume design department" of one of the main plants of the company, with additional study visits to two other plants. Participants included design engineers, manufacturing engineers, spare part manufacturers and the end users (production personnel). A number of interviews and workshops were conducted to investigate the existing AM digital flow and associated DfAM capabilities. The interviews and the workshops identified some critical hotspots, including AM skills, digital infrastructure, part testing and user-safety related challenges. Apart from the indirect observations and interviews, a separate study specifically focused on the work and information flow was also carried out. To restrict the scope of the study, the observational boundaries were determined to be the point where a new tool is requested as the starting point, and its final delivery to the end user as the ending point. Overall, the study involved two steps. First, the observations involved tools which were to be conventionally manufactured. The work and information flow observed was mapped between the two boundary points mentioned before. This is shown in Figure 3, marked as 1.

Second, preliminary investigations were made on how the conventional workflow would be affected with the introduction of AM. This was done by mapping generic AM specific design and manufacturing guidelines available in literature (e.g., [20,7]). This was then applied in practice onto three tools, which were previously manufactured by the company by conventional means. The tools were carefully selected based on their

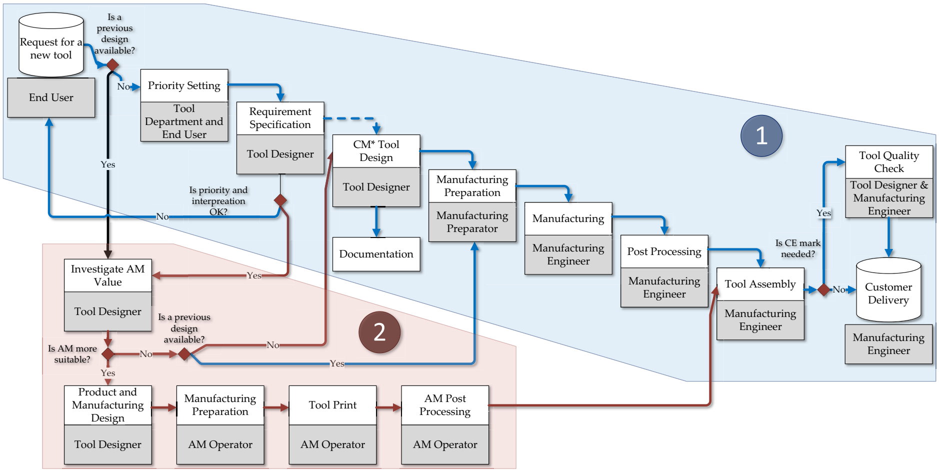

Figure 3. Observed workflows for tool manufacturing in a Swedish OEM. Flow marked as 1 relates to conventionally manufactured tools. Flow marked with 2 shows changes due to the introduction of AM. Reproduced from [6].

current use in the production line, aspects such as suitability to be additive manufactured etc. Further, the tools were redesigned keeping DfAM guidelines in mind, incorporating topology optimisation, ergonomic and sustainability improvements. Once the tools were printed and tested (if required), they were put to use in the production line. Some designs were iterated based on the feedback received from the end users. The aforementioned process was observed which was used to modify the generic AM process. The modification was iteratively integrated with the previously observed workflow related to the conventional manufacturing. This is shown in Figure 1 marked as 2. Note that the introduction of AM in the manufacturing portfolio creates a break in the pre-existing workflow between requirement specification and tool design, shown with the dotted arrow. In the new workflow, a new decision point is created where the suitability of AM as the manufacturing method is decided before it is manufactured.

3.1.2. Case 1: Observations

The nature of production tool design makes the process highly iterative and reliant on the experience of engineers and tool designers. This makes formally capturing the process a difficult task. Therefore, while the captured workflow shown in Figure 1 is based on observations, it is somewhat simplified and does not represent the workflow in granular detail. Further, the complexity of the process means that the resulting workflow representations can be highly complex for even simple parts such as a gear protector. A significant information which is generally tacit is therefore expected to be lost. A notable hotspot identified was the absence of PLM support for tools in the current process. Although the company effectively utilises PLM systems for managing parts related to its products, (although planned) the same is not used for production aids like tools yet. Incorporating PLM systems in this aspect could not only enhance the management of the design process but also enable the capture of design rationale and a wider range of data for record-keeping purposes. This would ultimately contribute to better quality assurance and quality control of such tools. However, during stakeholder interviews, some challenges were brought to light. Firstly, as mentioned earlier, the PLM systems currently being used are designed specifically for products, and employing the same frameworks for production tools may not be the most optimal solution. The tools will therefore need to be tailored which needs time. Potential areas of disruptions identified by the engineers through the interviews include concerns about increased bureaucracy and time consumption. Several tool designers expressed concerns that transitioning the workflow to a PLM system could potentially disrupt the agility of the tool design process, an important requirement for the future implementation of such a system. On the other hand, the interviews also indicated that the broader plan involved ongoing developmental work in this regard. Specifically on the development of a global tooling repository, which is currently in a test environment. While some teething issues are inevitable and are expected, risk mitigation strategies will be put in place to reduce disruption and maintain agility. When the whole supply chain is considered from a holistic perspective, all stakeholders agree that implementation of a PLM system will only help with the overall process. Further, the interviews indicated that a decision support tools which can be used in the early phases of a tool development process could be useful. Specifically, the engineers were interested in digital tools which can enable trade-off studies helping them choose between manufacturing methods.

3.2. Case 2: Digital process for printing with external suppliers

One of the important AM industrialisation enablers is local print on demand, i.e. local production close to the end user. While there are several benefits associated with local print-on-demand there are also significant challenges. Some possible benefits may include robust supply chains through alternative production, material savings through a reduction in tooling and the minimum number of ordered parts, i.e. (physical) stock optimisation, reduced transport, reduced lead time due to reduced manufacturing process steps and so on. Whereas, challenges include obtaining secure sharing of data for IP-sensitive designs when dealing with external service providers, and risk of excessive data management administration. This case was set-up primarily to study the aforementioned challenges.

3.2.1. Case 2: Study setup

To mimic a true industrial scenario, the project was set up with multiple Swedish companies and research institutes. The companies involved were; two OEMs in the role of customers, one material supplier, a dedicated company specialising in AM post processing, two research institutes as AM service providers and finally, a software company to support the project as a technical software provider. To put the use-case in context, three scenarios with increased complexity, inspired by conventional manufacturing were described as follows:

1. In-house manufacturing: The whole value chain is within the OEM.
2. External manufacturing with sub-suppliers.
3. Procurement phase & external manufacturing with sub-suppliers

In Table 1, the first two rows suggest the association between different disciplines & departments and the defined process steps, which is applicable for scenarios 1)-3). In rows 3 and 4 the corresponding association is made for the responsible organization /

Table 1. Process flow associations. CAD = Computer Aided Design, CAM = Computer Aided Manufacturing, CAE = Computer Aided Engineering (Functional (A, B)- or Process- (C) Simulation), QA = Quality Assurance, OEM = Original Equipment Manufacturer, AM-SP = AM Service Provider, HT= Heat Treatment, HIP = Hot Isostatic Pressing

Organization/ Department/ Discipline	**A** Product Design Functional Geometry	**B** Manufacturing Product Design, Layout	**C** Manufacturing Process Design	**D** Printing	**E** Post Manufacturing Processing
Ownership Dept	R&D/Product owner	R&D/Product owner	Production	Production	Production
Technical Discipline	CAD/CAE	CAD/CAM/CAE	CAM/CAE	Machine Operator	Machine Operator
Responsible Org	OEM	OEM or AM-SP	AM-SP	AM-SP	AM-SP
Sub Suppliers				Material Providers	HT, HIP, Machining

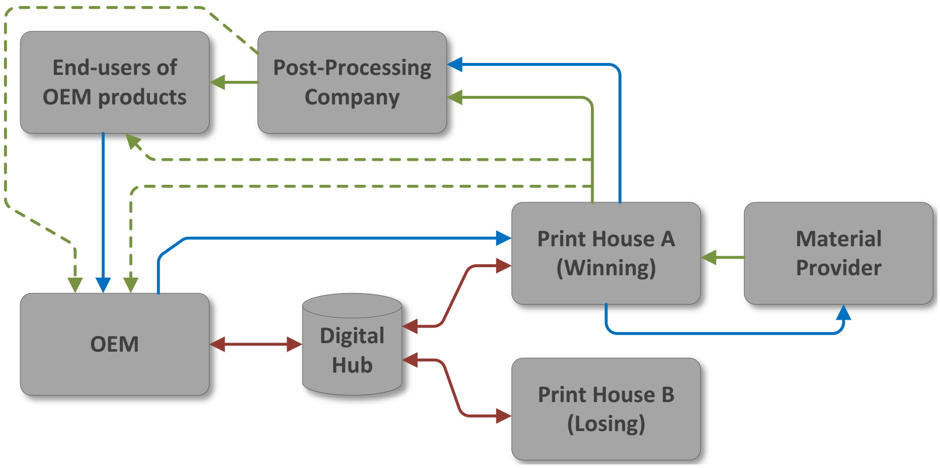

Figure 4. Physical and virtual (data exchange) process map on organisation level. From bidding phase to product in operation. The blue arrows are orders, red arrows data exchange and green arrows are physical deliveries (dotted green are alternative physical deliveries).

company, which is applicable to scenario 2). For the case of external manufacturing the "handshake" between the customer (OEM) and the supplier (AM Service provider (AM-SP)), depends on the type of agreement between the two parties. It can be $A \to B$, $B \to C$ or even $C \to D$, depending on the capabilities each organization has and of course the business model of the OEM. The next level of complexity is introducing a procurement phase with competing AM Service providers (Print houses), i.e., scenario 3). Here, separating who has access to which information becomes even more important. In Figure 4 a simplified flow chart with two competing print houses is shown. Finally, there could also be a varying degree of iteration loops, which further adds complexity to the physical and virtual flow.

3.2.2. Case 2: Observations

Secure sharing of data – OEM perspective The demonstrator showed a method for safely sharing IP sensitive data, with an external supplier in ordinary work. IP sensitive data could be CAD files, material properties, but also data from the manufacturing process etc. The method developed also demonstrated the possibility to control what partner in the process has access to what information, meaning, one could choose to share only what is needed for each step in the manufacturing process. In ordinary work, non disclosure agreement (NDA)s, normally are in place with manufacturing partners within the company's normal network of suppliers and becomes not an obstacle for fast order handling. In the situation of for example a spare part sales where a manufacturer is geographically close to the customer in need of the spare part might be preferred for short delivery time etc, the NDA not being in place might become an obstacle with risk of delaying the delivery. The outcome from the project also demonstrated quality assurance of manufactured parts as well as possibility for tracing of materials. This is critical functionality, especially if the manufactured part in question is related to safety of person, environment, equipment etc.

Management of cross functional IT systems When a new cross functional software is installed in an organisation, it is important to have a clear owner. Especially for the type of software that has a lot of questions regarding access, and has both internal and external personnel involved. For instance, while the daily work for designers at R&D enables a dialog with sub suppliers, and therefore makes it easy for them to handle the technical questions, however, when it comes to pricing and the back flow containing traceability documents the content may be more suitable for personnel from production. The fact that the purchasers may have prices, agreements, and the name of contacts at the sub suppliers, perhaps makes them more suitable to be the owners of this type of software within an organisation.

4. Digital hotspots and risk analysis

From the two case studies and observations made, a number of hotspots were identified. While a number of them were to do with skills, training and other technical aspects of AM, the focus of this paper is on the digital aspects only. One domain however where the digital and organisational hotspots overlap is that of knowledge management. Design knowledge is often tacit and therefore is not transferable from manufacturing method to method. This is especially a problem when the method is radically different requiring a new way of product development such as in AM. Such knowledge must be captured systematically, for instance by the use of PLM. PLM integration could enable a controlled scale-up of printing with proper traceability and also help in compliance with quality standards wherever necessary. Further significant amount of information can be systematically stored in PLM systems which can be used in training Artificial Intelligence (AI) models in the future leading to more robust mechanisms of decision making. Decision support tools must also be used to aid decision making. While it may be easy to make decisions when only 2-3 aspects (such as cost, lead time, performance) are involved, it may become significantly challenging when other criteria are included such as sustainability, reliability, flexibility and so on. Designers may need training on "design thinking" approaches as product design for additive manufacturing can be significantly more complex. Unlike traditional design processes where the usually post design tasks, such as manufacturing may only be considered at later stages, in AM the design considerations for manufacturing, assembly, and functionality/performance are correlated and

Table 2. The advantages of additive manufacturing, the factors which are influenced by the advantages and the associated risks in the digital domain

Advantages	Influencing Factor	Risk
Design Freedom	Engineering Design Process	Digital Workflow Disruptions Improper requirements management Improper knowledge management Lack of decision support
	Design Complexity	Product Integrity Post Processing Product reliability Product Sustainability
	Regulatory Compliance	Certification and testing
High Printing Efficiency	Printing in-house or by supplier	Intellectual property rights Data theft and reverse engineering Traceability Quality Control Lead time
Distributed Manufacturing	Printing by supplier	Supply Chain Risks Unskilled operator
Process and material flexibility	Material variety and complexity	Process repeatability
		Post-Processing and Finishing

not independent. This also highlights the potential workflow conflicts when a company may have both conventional and additive manufacturing in their manufacturing portfolio. The complexity arises from the design freedom AM offers. Further, the complexity may introduce risks to product integrity, reliability, sustainability and the complexity of post processing. When companies switch from conventional manufacturing to additive manufacturing, the risks related to these may be determined and reduced by ensuring appropriate digital capabilities related to simulation exist. Related to such risk are also aspects of certification and testing. Digital capabilities of simulation and testing may help mitigating them.

Another advantage of additive manufacturing is the potential efficiency of printing. However, this could be influenced by a number of exogenous factors such as whether the part is being printed in-house or by an external supplier. If it is being printed by an external supplier, it is important to clarify who owns the intellectual property rights and how is traceability maintained. Similarly, another exogenous factor could be how a company's digital infrastructure is set up. For example, if a company's PLM system is set up for conventional manufacturing or conventional supply chain, it may not be fully suited for using AM or scenarios described in Section 3.2. Further, if the data transfer capabilities are setup between the print houses, material suppliers and testing agencies, risks related to data theft, reverse engineering must be taken into account. Maintaining material traceability for quality assurance, transfer of quality control data etc are other risk factors which must be taken into account by a company looking to implement AM. When it comes to distributed manufacturing, where print houses are used instead of in-house printing, risks related to disruptions in supply chain (e.g. single print house), and quality risks may be considered. In general, AM also requires vastly different types of parameters to be recorded and a vastly different process flow than conventional manufacturing, any form of digital infrastructure implemented therefore should consider the aforementioned risks. A company should look to simplify supply chain by either having in-house (on demand) printing or having a clearer pipeline for printing with local print houses.

Finally, the advantage AM provides in terms of process and material flexibility has also got its challenges. The vast number of materials available creates risk on ensuring process repeatability. The digital infrastructure to support AM in a company must account for recording traceability data for material. Further, AM may also require post-processing, which is another step which must be supported by the digital infrastructure created. This may also include aspects such as testing and certification, not just for regulatory compliance as stated earlier but also process reliability and repeatability.

The aforementioned factors lead to a set of risk criteria that indicate what may be necessary for a successful implementation of additive manufacturing in a company. These are captured in Table 2. For a successful implementation of AM in a company, these risks must be mitigated. These risk factors were recorded based on the observations made in the previously discussed cases.

5. Conclusion

Companies are adopting AM at a rapidly increasing pace. While the uptake can be attributed to the many advantages the technology offers, they also come with significant digitalisation related challenges which post risks to its successful implementation in companies. Many companies are unable to foresee these digitalisation related risks which leads to either complete failure of implementation, or extremely high rectification costs. In this paper we presented learning’s from a long running project in Swedish OEMs. First observations are made from the two cases presented which are mapped against potential risks. Each of the observations lead to certain risks. Initial observations show that this type of evaluation can give a snapshot view of issues that may not be obvious but may have significant ramifications when it comes to the success of AM. Objective evaluation of the risks in a company before implementing AM, can increase the chance of success. Further, it can help create decision-support tools to help managers evaluate digitalisation related risks surrounding additive manufacturing and in companies with existing manufacturing ecosystem. The paper is based on empirical findings in industrial cases, also reported in the DIDAM Digital Model Guide (Digital Model Guide, 2023).

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References

[1] Huang Y, Leu MC, Mazumder J, Donmez A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. Journal of Manufacturing Science and Engineering. 2015 02;137(1):014001. Available from: https://doi.org/10.1115/1.4028725.

[2] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, et al. Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints. CIRP Annals. 2016;65(2):737-60.

[3] Mallalieu A, Hajali T, Isaksson O, Panarotto M. The Role of Digital Infrastructure for the Industrialisation of Design for Additive Manufacturing. Proceedings of the Design Society. 2022;2:1401–1410.

[4] Martinsuo M, Luomaranta T. Adopting additive manufacturing in SMEs: exploring the challenges and solutions. Journal of Manufacturing Technology Management. 2018;29(6):937-57.

[5] Kulkarni P, Kumar A, Chate G, Dandannavar P. Elements of additive manufacturing technology adoption in small-and medium-sized companies. Innovation & Management Review. 2021;18(4):400-16.

[6] Hajali T, Mallalieu A, Brahma A, Panarotto M, Isaksson O, Stålberg L, et al. INFORMATION FLOW ANALYSIS ENABLING THE INTRODUCTION OF ADDITIVE MANUFACTURING FOR PRODUCTION TOOLS-INSIGHTS FROM AN INDUSTRIAL CASE. Proceedings of the Design Society. 2023;3:2315–2324.

[7] Diegel O, Nordin A, Motte D. In: Additive Manufacturing Technologies. Singapore: Springer Singapore; 2019. p. 19-39.

[8] Mellor S, Hao L, Zhang D. Additive manufacturing: A framework for implementation. International Journal of Production Economics. 2014;149:194-201. The Economics of Industrial Production.

[9] Borgue O, Müller J, Leicht A, Panarotto M, Isaksson O. Constraint Replacement-Based Design for Additive Manufacturing of Satellite Components: Ensuring Design Manufacturability through Tailored Test Artefacts. Aerospace. 2019;6(11).

[10] Hague R, Dickens P, Hopkinson N. Rapid manufacturing: an industrial revolution for the digital age. John Wiley & Sons; 2006.

[11] Birtchnell T, Urry J. A new industrial future?: 3D printing and the reconfiguring of production, distribution, and consumption. Routledge; 2016.

[12] Rylands B, Böhme T, Gorkin III R, Fan J, Birtchnell T. The adoption process and impact of additive manufacturing on manufacturing systems. Journal of manufacturing technology management. 2016;27(7):969-89.

[13] Zimmermann N, Lentes J, Schaper S, Werner A. Comparison of Process Chains of Additive and Conventional Manufacturing. In: Huang CY, Dekkers R, Chiu SF, Popescu D, Quezada L, editors. Intelligent and Transformative Production in Pandemic Times. Cham: Springer International Publishing; 2023. p. 151-62.

[14] Belkadi F, Vidal LM, Bernard A, Pei E, Sanfilippo EM. Towards an Unified Additive Manufacturing Product-Process Model for Digital Chain Management Purpose. Procedia CIRP. 2018;70:428-33. 28th CIRP Design Conference 2018, 23-25 May 2018, Nantes, France.

[15] Panfili G. Industrialisation and Field Experience of Gas Turbine Components Made By Additive Manufacturing. In: Gas Turbines for Energy Network Symposium; 2019. .

[16] Aheleroff S, Xu X, Zhong RY, Lu Y. Digital twin as a service (DTaaS) in industry 4.0: An architecture reference model. Advanced Engineering Informatics. 2021;47:101225.

[17] Kim DB, Witherell P, Lipman R, Feng SC. Streamlining the additive manufacturing digital spectrum: A systems approach. Additive Manufacturing. 2015;5:20-30.

[18] Mies D, Marsden W, Warde S. Overview of additive manufacturing informatics:"a digital thread". Integrating Materials and Manufacturing Innovation. 2016;5(1):114-42.

[19] Bonham E, McMaster K, Thomson E, Panarotto M, Müller JR, Isaksson O, et al. Designing and Integrating a Digital Thread System for Customized Additive Manufacturing in Multi-Partner Kayak Production. Systems. 2020;8(4). Available from: https://www.mdpi.com/2079-8954/8/4/43.

[20] Gibson I, Rosen D, Stucker B. In: Generalized Additive Manufacturing Process Chain. New York, NY: Springer New York; 2015. p. 43-61.