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Additive Manufacturing enabled Digital Inventory: Perceived Benefits & Challenges

A Single-Case Study

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Abstract

Background: Industry 4.0 brings new technologies said to improve organizations' supply chain performance. Additive manufacturing (AM) and information and communication technologies have received much attention in recent years. A combination of the two has recently surfaced in literature and captured the interest of large manufacturing organizations such as Siemens Energy. Namely, AM-enabled Digital Inventory (DI).

Problem: AM is considered a new manufacturing method and is still under development, thus, industries have yet to realize AM's full potential. DI has been presented as a suggested tool to maximize AM's potential. However, existing research on DI is scarce. For manufacturers to properly evaluate DI and decide on implementation more information is needed.

Purpose: To aid decision-makers in the navigation of DI implementation, we have conceptually explored practitioners' perceptions of the DI concept and related benefits and challenges. To ultimately allow organizations to obtain the full potential of AM, and thereby increase supply chain performance and remain competitive in the transition to Industry 4.0.

Method: Ontology – Relativism, Epistemology – Constructivism, Qualitative, Inductive, Exploratory, Single-case study, 8 semi-structured interviews, 10 semi-structured group interviews, Snowball sampling, Purposive sampling, Thematic analysis.

Conclusion: With this research, we were able to establish that the DI concept should function as a system that allows for easier sharing and access of information. Benefits found: Process optimization, reduced risk, and cost, further development, and increased competitiveness. Challenges found: rules and regulations, change management, operations issues, strategy, profitability, system issues, and post-processing. Ultimately, to obtain the benefits, trade-offs in lead time, capacity cost, and inventory costs need to be considered. Before calculations can commence components suitable to include in a DI needs to be established.

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List of Abbreviations

Abbreviation	Meaning
AM	Additive manufacturing
CAD	Computer aided design
CM	Conventional manufacturing
DI	Digital Inventory
DSP	Digital spare parts
ICT	Information and communication technology
IP	Intellectual property
MRQ	Main research question
SE	Siemens Energy
SLM	Selective laser melting
SRQ	Supporting research question

1. Introduction

In this section, the reader is introduced to the research topic. This section includes the background, problem, purpose of the research, research questions, and the set delimitations. A terminology section has also been added to enhance the reader's understanding of this research.

1.1 Background

The fourth industrial revolution, industry 4.0, is here. This can be seen through emerging technologies and digital solutions aimed at increasing efficiency and productivity (Frank et al., 2019). The technological advancements made, and changes in customer requirements, are increasing the competition for organizations worldwide (Ghadge et al., 2020). Organizations are now focusing more on their supply chain and hence, supply chain management. More specifically, organizations are experiencing difficulties in their spare parts supply chain (Khajavi et al., 2014). Heavy investments are needed due to the need for businesses to hold large inventories in order to reach good fulfilment rates and reliability.

The ever-ongoing challenge within supply chain management is to increase service value toward customers while cutting production and/or delivery costs (Holmström et al., 2010). Supply chain innovations that improve efficiency both in terms of service and operations are thus becoming increasingly important (Luomaranta & Martinsuo, 2020). The concept of industry 4.0 includes several technologies that may allow organizations to improve supply chain performance (Ghadge et al., 2020). One technology is additive manufacturing (AM) (Ghadge et al., 2020; Frank et al., 2019). AM is a technology used for smart manufacturing (Frank et al., 2019), where layer upon layer is built up three-dimensionally (Togwe et al., 2019; Guo & Leu, 2013) usually from computer-aided-design (CAD) data files (Gupta et al., 2020). AM is said to have the potential to reconfigure supply chains (Luomaranta & Martinsuo, 2020; Ghadge et al., 2018), as AM may enable organizations to produce on-demand and customize while cutting costs (Holmström et al., 2010). Making AM particularly useful for the spare parts supply chain since the spare parts supply chain operates on a demand-pull basis (Li et al., 2017).

As the demand for AM technology increases it becomes significantly more important for organizations to find a way to adapt (Wang et al., 2019b). The digital transformation following the adoption of AM technology may encourage further attempts at digital development. This to

further integrate and facilitate the AM technology and respond to the demand. Smart manufacturing technologies such as AM combined with information and communication technologies (ICT) can result in an integration of physical objects and the virtual dimension of factories (Gupta et al., 2020; Kim & Park, 2017). Thus, connecting the AM technology with an ICT can contribute to the realization of an AM-enabled Digital Inventory (DI) (Araújo et al., 2021). A DI could, apart from contributing to digital advancement, have an impact on the development time and cost relating to the production cycle (Wang et al., 2019a). Furthermore, a DI could help with realizing the full advantage of adopting AM technology (Mashhadi et al., 2019). More specifically, a DI has the potential to significantly reduce costs (Araújo et al., 2021). Adopting a DI in the spare part supply chain is therefore potentially a response to the ever-ongoing challenge within supply chain management.

Throughout this research when we talk about a DI, we are referring to an AM-enabled DI.

1.2 Problem

Although AM has been developed for decades (Chan et al., 2018; Rogers et al., 2016; Guo & Leu, 2013; Holmström et al., 2010), it is still considered an emerging technology (Wagire et al., 2020; Frank et al., 2019). Previous research has focused on AMs' usefulness in the spare part supply chain context. Hence, a similar context will be used in our research. Moreover, previous research points out that industries are yet to realize the full potential of AM (Guo & Leu, 2013), thus, more research on the best use of AM is called for (Ghadge et al., 2018; Frank et al., 2019). One suggestion on how to use AM and maximize its potential has been presented through previous literature as a DI (Araújo et al., 2021).

A DI is made possible through advancements in AM and ICT. However, ICTs are also considered emerging (Wagire et al., 2020; Frank et al., 2019). Thus, the concept of DI, is still in the process of development. Previous literature on DI is scarce indicating that it is a new concept that is yet to be widely adopted by organizations. No previous research has investigated the meaning of a non-public DI with a centralized approach. Yet a centralized approach to AM has been described as the most feasible (Holmström et al., 2010). Thus, exploratory research aimed at describing the DI concept with a centralized approach can be considered appropriate.

Before starting the digital transformation in the supply chain that the implementation of a DI is, it is important to understand the related potential benefits and challenges of AM and DI (Araújo et al., 2021). Previous literature about benefits and challenges connected to DI is scarce. Thus, the benefits and challenges of a DI need to be explored to gain further knowledge about the concept and how it may be implemented to utilize the full potential of AM. Understanding the benefits and challenges may also provide insights into why research is positive towards DI, but manufacturers are yet to widely adopt this technology.

1.3 Purpose

The purpose of this research is to conceptually explore the perceived benefits and challenges of DI in the spare part supply chain, to aid decision-makers in the navigation of this emerging technology. A better understanding of how to navigate this emerging technology is expected to aid in the adoption of DI and allow organizations to realize more of AM's potential. To ultimately, enable organizations to remain competitive in the transition towards industry 4.0 and respond to the ever-ongoing supply chain challenge. As well as contributing to the theoretical knowledge concerning DI. Thus, our main research question (MRQ) is as follows:

***MRQ:** How do industrial practitioners in large manufacturing organizations perceive benefits and challenges of the AM-enabled DI concept?*

To be able to answer the MRQ we must first develop an understanding of what a DI entails by investigating the unexplored concept of DI to fill the literature gap. Thus, the first question this research must concern itself with is the supporting research question (SRQ) which reads as follows:

***SRQ:** How do industrial practitioners in large manufacturing organizations perceive the AM-enabled DI concept?*

To answer our research questions, we will work together with Siemens Energy (SE) to see what benefits and challenges can be expected in the realization of a DI. Important to note is that we are not aiming to build a theoretical model, but rather contribute with theoretical knowledge. In the discipline that this research takes place, theories are often not used to understand findings in the same way as in other disciplines e.g., in pure management or business research. Instead, we will mainly build on existing theoretical knowledge in a similar manner as previous studies

within the same field have done (see e.g., Araújo et al., 2021; Chekurov et al., 2021; Chekurov et al., 2018; Ballardini et al., 2018). A very simple model will however be used briefly to explain the DI concept.

1.4 Siemens Energy

Since SE is a major and established player in the industrial AM field, we want to be upfront about our relationship with SE. One of the authors has previously worked at SE. Thus, it was natural for SE to ask us to conduct research with them. We believe that without this personal relationship it would have been difficult to conduct a single-case study with such a major organization and get the number of interviews that we did. The choice of doing a single-case study will be further elaborated on in Chapter 3. But is mainly due to SE's perception of DI as a competitive advantage, and thus, unwillingness to collaborate with competitors. SE's wish was for us to conduct research in the DI realm. Together with SE, we identified a few possible research avenues all with research gaps (some of which were difficult to conduct, we will elaborate further on this in Chapter 7). But decided together with SE to research the DI concept and related benefits and challenges. Throughout this research an industry expert at SE has been supervising and guiding us, providing valuable insights into this advanced manufacturing method.

SE has its origin in Germany and is constituted by the former gas and power section at Siemens AG (Siemens Energy, 2022). Siemens AG was founded in 1847 and SE was established in 2020. SE is considered one of the larger players in the global energy industry with about 16% of the world's energy based on SE technology, locations in more than 90 countries, and about 91000 employees globally. The core business for SE in Finspång is to manufacture, sell, and maintain gas and steam turbines. However, SE is also involved in the transmission business, industrial applications, and new energy business.

We are focusing on the AM technology that SE is currently working with and developing in Finspång, mainly in the spare part production for their service function. AM is said to be most suitable in spare part production (Togwe et al., 2019). SE uses metal AM as the turbine components need to be able to withstand high temperatures. Metal AM is not considered a mature technology (Lezama-Nicolás et al., 2018), and still needs development. The AM technology SE uses is called selective laser melting (SLM) which can also be referred to as

direct metal laser melting (Siemens Energy, 2022). SLM is a technique that uses a high-power density laser to fuse and melt powder into metal components (Frandsen et al., 2020). This method is preferred since it has the ability to fully fuse and melt the powder into 3-dimensional parts and create components with up to 99,9% density (Abdulhameed et al., 2019). SLM can produce components with complex geometries that would be too advanced to produce with conventional manufacturing (CM) methods (Frandsen et al., 2020). Thus, SLM is deemed necessary to produce SE's complex and demanding components. Metal AM and specifically SLM will hence, be a delimitation of this research.

Due to SE's use of SLM in combination with the components demanding placement in the finished product, extensive post-processing is often necessary. Hindering a decentralized or distributed approach. Our research thus focuses on a centralized approach. Which has been described as the most feasible (Holmström et al., 2010). Additionally, the nature of the components manufactured by SE, demands that any digitalization of the value chain would have to be of a non-public nature to not conflict with export- and patent- laws. Thus, our research focuses on a non-public DI.

1.5 Terminology

Centralized – A production approach where the AM machinery is in one single location (Khajavi et al., 2014). Serving the points of need from that location.

Decentralized – A production approach that uses more than one production facility, located close to major markets (Khajavi et al., 2014). E.g., The AM machine can be placed on a national or regional basis.

Distributed – A production approach where each consumption point is equipped with AM machinery to produce components (Khajavi et al., 2014). In a distributed AM approach the AM machine is movable (Eyers, 2020). To be movable the printer could be placed in a container.

2. Literature Review & Frame of Reference

The sub-headings in this section each aim to contribute to the reader's understanding of the research topic, by presenting the theoretical knowledge necessary to conduct this research. Furthermore, the sub-headings are presented in the same order as the research questions, to allow a logical order for the reader.

The theoretical framework of this research has been developed as per a traditional literature review (Easterby-Smith et al., 2018). Meaning that previous literature on the chosen topic has been summarized (Frey, 2018). We searched for information on the topic with the aid of selected keywords, visible in Table 1. To ensure the sources used were of relevance, the searches were delimited to not be older than 2011, as that was the year when the concept of industry 4.0 was coined (Frank et al., 2019). As previously established, industry 4.0 includes AM and ICT (Ghadge et al., 2020; Frank et al., 2019). The coining of industry 4.0 can be assumed to have accelerated the development of literature on the topic. However, we also used older sources when deemed relevant e.g., when sources occurred (often frequently) in other literature.

Table 1. Search parameters for the theoretical framework

Search Parameters	
Databases	Google Scholar, JU Primo, Scopus
Keywords	3D printing*, Additive manufacturing, industry 4.0, Additive manufacturing sustainability, Cloud manufacturing, Additive manufacturing Cloud, Digital inventory additive manufacturing, Digital spare-parts additive manufacturing platform, Smart additive manufacturing, Additive manufacturing Challenges/Opportunities/Benefits/Barriers
Sources	Academic articles, Academic books
* For all searches we used both the phrase additive manufacturing and 3D printing	

2.1 Introduction to Additive Manufacturing

AM bears many names e.g., 3D printing, digital manufacturing, and rapid manufacturing (Rogers et al., 2016). AM refers to a process that constructs three-dimensional parts by adding layer by layer of a material, based on digital model data (often CAD files) (Togwe et al., 2019; Guo & Leu, 2013). The additive nature of AM differentiates the manufacturing process from other subtractive processes where materials are instead removed (Luomaranta & Martinsuo, 2020; Guo & Leu, 2013). AM is used in several industries e.g., in jewelry, biomedical, automotive, and aerospace industry (Rogers et al., 2016). A commonly known example of AM

is the usage of AM in the aviation industry (Togwe et al., 2019; Ballardini et al., 2018). Where machine components and spare parts are produced additively, reducing the cost and time of ordering replacement parts (Ballardini et al., 2018). Previous research on AM can most prominently be seen in the spare part supply chain (e.g., Khajavi et al., 2020; Ballardini et al., 2018; Holmström et al., 2010). This is due to the possibility of reducing large inventory holdings necessary in conventional spare part production, by implementing AM (Togwe et al., 2019).

2.1.1 Metal Additive Manufacturing

AM can be used on a variety of materials such as plastic, ceramic, biomaterial, sandstone, and metal (Rogers et al., 2013). The raw materials used can be in various forms – solid, liquid, and powder (Abdulhameed et al., 2019). There are several different AM techniques appropriate for various materials and material forms. Figure 1 below provides a classification of AM techniques suitable for different material forms.

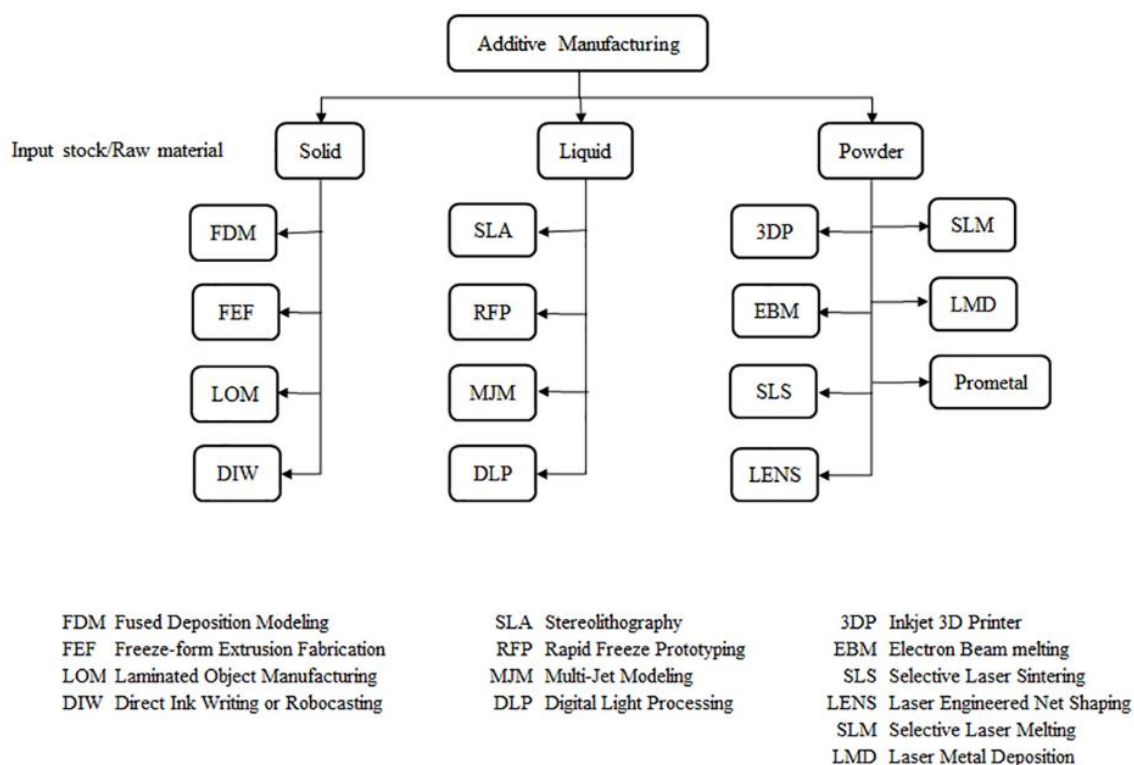


Figure 1. Classification of AM techniques depending on raw material form (Abdulhameed et al., 2019, p. 4)

Depending on the type of component organizations are looking to produce various techniques will provide different properties to the product (Abdulhameed et al., 2019). Plastic AM is considered mature whereas metal AM is not (Lezama-Nicolás et al., 2018). Much focus is

currently being placed on metal AM based on powder-bed fusion techniques, due to leading manufacturers' adoption of such technologies (Kretzschmar et al., 2018b). LM, Electron beam melting (EBM), and Laser metal deposition are the appropriate techniques for metal AM of functional parts and tooling (Abdulhameed et al., 2019). All mentioned techniques are powder-based but differ in material preparation. SLM and Electron beam melting are powder-bed fusion techniques (Frandsen et al., 2020), whereas Laser metal deposition injects powder through a nozzle (Abdulhameed et al., 2019). Powder-based metal AM is highly dependent on the powders' characteristics as it impacts the quality of the finished product (Qian, 2015). Adding the need for additional knowledge to an already advanced manufacturing method.

SLM is considered one of the most promising metal AM techniques (Wang et al., 2020). It is a technique that heats and fuses metal powder into components (Frandsen et al., 2020). This technique is often used in the aerospace, automotive, and medical industry. Parts can be created with up to 99,9% density (Abdulhameed et al., 2019), and complex geometries not possible to produce with CM methods can be produced using SLM (Frandsen et al., 2020). However, SLM is considered one of the more costly AM production methods (Abdulhameed et al., 2019). Metal AM in general requires post-processing due to the poor surface quality of printed parts (Maleki et al., 2021; Mellor et al., 2014). The surface quality can affect the mechanical properties of parts such as corrosion resistance, wear- and scratch- resistance, fatigue performance, and dimensional accuracy (Maleki et al., 2021). For some AM techniques, such as SLM, support structures are necessary to print. Amplifying the need for post-processing activities. There are several post-processing options available for metal AM (Maleki et al., 2021). Metal AM post-processing can be classified into four categories – material removal, no material removal, coatings, and hybrid treatments. The categories include but are not limited to various heat treatment options, and chemical treatment options (Maleki et al., 2021; Mellor et al., 2014).

2.2 Introduction to the Spare Parts Supply Chain

The supply chain can be explained as the flow of products/services, information, and finances that occurs between and within entities (Mentzer et al., 2001). Strong supply chain performance is linked with strong market positioning and competitive edge, making it an important consideration for organizations (Delic et al., 2019). The performance of the supply chain can be established by measuring its efficiency and effectiveness. However, due to the specific characteristics and features of spare parts the management of them in the supply chain can differ

compared to other commodities and raw materials (Tapia-Ubeda et al., 2020). The production of spare parts can be considered an essential source of revenue for many organizations and can amount to about 25% of revenue and 40-50% of profit for organizations driven by manufacturing (Achetoui et al., 2019; Wagner & Lindemann, 2008). Moreover, the production and management of spare parts are important for organizations since they can limit the impact of equipment downtime and following detrimental effects that it may have on organizational results (Tapia-Ubeda et al., 2020). However, production is also linked to challenges in supply chain operations and may therefore influence the processes associated with supply chain management (Achetoui et al., 2019). Spare part production is related to fluctuations and unpredictable demand which therefore generates a challenge in creating accurate forecasts for supply chain operators (Wagner & Lindemann, 2008). Often leading to the necessity of holding a large inventory (Togwe et al., 2019). Therefore, to successfully execute the production and management of spare parts organizations ought to install management systems that operate effectively and responsively to accomplish customer demands, and financial- and operational-excellence (Achetoui et al., 2019).

2.3 AM-Enabled Systems

Previous literature has not provided a collective name for the concepts of cloud-based AM, AM-enabled virtual libraries, and AM-enabled DI. In this research, we have chosen to refer to them collectively as AM-enabled systems.

To the best of our knowledge, a limited amount of literature describes what an AM-enabled DI is. In this section, we have therefore gathered information on various AM-enabled systems. This will serve as the existing theoretical knowledge necessary to analyze our findings in Chapter 5. Moreover, all AM-enabled systems can be understood as ICT. When implementing AM, suitable ICT infrastructure is necessary (Durão et al., 2017), as it provides the connection between the physical and virtual dimensions of a factory (Gupta et al., 2020; Kim & Park, 2017).

Following recent years' exponential growth in AM technology, various AM-enabled systems have emerged. *Cloud-based AM* has been suggested to increase the utilization of AM resources and technology, reduce manufacturing costs, and be a helpful tool for scheduling production activities (Wang et al., 2019b). The cloud-based AM functions in a way where the customer

uses the internet to transmit the design to the AM service provider, which triggers a printer, then the component is printed, and the finished product is sent back to the customer. Thus, consumers can access AM technology without having to invest in machinery (Baumann & Roller, 2017). When sharing information in cloud-based AM, data security issues such as intellectual property (IP) rights need to be considered. Cloud-sharing the AM technology can be utilized by many organizations by providing their customers access to AM technology (Wang et al., 2019a). While allowing the AM service provider to potentially reduce unit cost by receiving multiple printing tasks from various customers to optimize the printing space (Wang et al., 2019b). Simply put, the cloud-based AM provides a market platform for several types of customers and AM service providers. An example of such a platform in Sweden is PostNord's 3D printing offering (see. PostNord, n.d.). This type of AM-enabled system has a service-oriented focus (Baumann & Roller, 2017).

Another way to service customers using AM is to allow customers access to *virtual libraries* of AM components (Ballardini et al., 2018). However, AM-enabled systems that make CAD files publicly available, such as in the case of cloud-based AM and virtual libraries, may raise questions regarding IP rights (Ballardini et al., 2018). Legal uncertainties regarding CAD patents and harmonization across countries may hinder businesses from adopting publicly open virtual libraries and cloud-based AM.

Another AM-enabled system has been identified by Araújo et al. (2021), as a smart DI that may be utilized non-publicly/internally by organizations as a way of realizing a digital value chain. The DI would work as a digital storage space for digital files containing product information which allows for on-demand AM production. The DI concept is thus similar to virtual libraries; however, the catalogue of CAD files is not necessarily publicly available. Moreover, keeping digital files in a DI and using it as a replacement for physical inventory can be used as a tool to significantly reduce related costs and increase product availability (Verboeket & Kirkke, 2019). Organizations can use digital inventories to better respond to fluctuations in demand and contribute to security in the supply chain (Araújo et al., 2021).

Both virtual libraries and digital inventories would consist of *digital spare parts* (DSP). Chekurov et al. (2018, p.95) described DSP as “A concept in which defective components are replaced by manufacturing spare parts close to the location of need from 3D model data that are transferred by networks with the main consequence of reducing repair time, delivery time,

and costs, emissions, and inventory”. Indicating the need for a decentralized or distributed production, to be close to the location of need. This necessity may however be questioned. Most current AM technology demands post-processing (Mellor et al., 2014), which hinders a distributed approach and can also hinder a decentralized approach. Kretschmar et al. (2018a) mean that DSP can be used within any type of manufacturing approach. I.e., parts can be stored digitally whether produced in a centralized, decentralized, or distributed manner. However, the centralized approach has been described as the most feasible in previous AM literature (Holmström et al., 2010).

2.4 Benefits Related to AM & AM-enabled Systems

Previous literature exploring the benefits of DI is scarce and a limited amount of previous literature explicitly explores benefits from a centralized approach. To build the theoretical knowledge necessary to analyze our findings in Chapter 5 we have summarized literature covering benefits related to AM and AM-enabled systems from various manufacturing approaches in the sections below. The two have been divided as AM is a production method whereas an AM-enabled system, is a system enabled by the production technique. For example, the benefit identified by Ballardini et al. (2018) called centralized product data is a benefit obtained through virtual libraries. The AM production method does not have the ability to centralize data, for that an AM-enabled system is needed.

Additionally, to provide the reader with further clarity, the benefits derived from previous literature have been summarized and presented in Table 2 below. Along with a brief description of each study, what the benefit concerns, and the stated manufacturing approach.

Table 2. Benefits Derived from Previous Literature

Authors	Description of Study	Benefits	Benefits Concern	Manufacturing Approach
(Holmström et al., 2010)	Conceptually compares centralized and decentralized AM spare-parts manufacturing	<ul style="list-style-type: none"> On-demand production Reduce physical inventory Reduced need of tooling Small batches are economical Less process wastes Shorter supply chains 	AM	Centralized and decentralized
(Mellor et al., 2014)	Explored an implementation framework for AM	<ul style="list-style-type: none"> Design optimization – functionality & weight Low volume production Shorter supply chain 	AM	Centralized
(Gebler et al., 2014)	Presents a global sustainability perspective on AM technologies	<ul style="list-style-type: none"> Less process wastes Reduced energy consumption Reduced emissions Reduced labor in production 	AM	Centralized and decentralized
(Oettmeier & Hofmann, 2016)	Analyzes the effects of AM on supply chain management, processes, and parts	<ul style="list-style-type: none"> Additional functionality of products Reduce no. of components Reduced no. of suppliers Versatile machinery Small batches are economical 	AM	Not considered
(Thompson et al., 2016)	Identifies constraints, considerations and opportunities when designing parts for AM	<ul style="list-style-type: none"> Increased design freedom Increased functionality Customization Reduce physical inventory 	AM	N/A
(Ford & Despesse, 2016)	Explores public data to identify advantages and challenges related to AM and sustainability	<ul style="list-style-type: none"> Less process wastes Increased functionality of part Reduced weight of part 	AM	Not considered
(Holmström & Gutowski, 2017)	Assessed environmental implications of AM on operations and supply chain management	<ul style="list-style-type: none"> Less process wastes Reduce physical inventory On-demand production 	AM	Not considered
(Ballardini et al., 2018)	Conceptually explores AM-enabled publicly available virtual libraries related challenges	<ul style="list-style-type: none"> Improve availability of parts Centralize product data Facilitate purchasing process 	Virtual libraries	Not considered
			AM	
(Chekurov et al., 2018)	Conceptually explores benefits of AM DSP	<ul style="list-style-type: none"> Reduced joints Increased quality of parts 	AM	Distributed
		<ul style="list-style-type: none"> Reduce transportation time & cost Reduce physical inventory 	DSP	
(Kretschmar et al., 2018a)	Evaluating the readiness of AM DSP	<ul style="list-style-type: none"> Reduce physical inventory 	DSP	Not considered
		<ul style="list-style-type: none"> Flexibility On-demand production 	AM	
(Kretschmar et al., 2018b)	Developed a decision support system for the validation of metal powder bed-based AM applications	<ul style="list-style-type: none"> Reduced lead-times Reduced operational costs 	AM	Not considered
(Peng et al., 2018)	Discusses AM energy consumption and environmental impact	<ul style="list-style-type: none"> On-demand production 	AM	N/A
(Togwe et al., 2019)	Identified what value AM offers compared to conventional in an aviation use case	<ul style="list-style-type: none"> Reduce inventory risk Reduce physical inventory Reduced labor in production Flexible 	AM	
(Wang et al., 2019a)	Explained cloud-based AM	<ul style="list-style-type: none"> Diminish development time 	Cloud-based AM	Decentralized
		<ul style="list-style-type: none"> Less process wastes 	AM	
(Gupta et al., 2020)	Discusses AM supply chain cybersecurity and risks	<ul style="list-style-type: none"> Reduced no. of suppliers Shorter supply chain Lean – less process waste & reduced lead-times Agility in production 	AM	Centralized, decentralized, and distributed
(Javaid et al., 2021)	Identified environmental benefits of AM	<ul style="list-style-type: none"> Less process wastes Reuse material Reduce physical inventory Reduced energy consumption Lighter parts 	AM	Not considered
(Araújo et al., 2021)	Characterized the impacts of smart AM on production and value chains	<ul style="list-style-type: none"> Less process wastes Flexible 	AM	Not considered
		<ul style="list-style-type: none"> Reduce physical inventory Possibility of being close to point of consumption 	DI	
This research will...	Conceptually explore benefits related to AM-enabled DI	<ul style="list-style-type: none"> See findings & analysis for the benefits we identified 	DI	Centralized

2.4.1 Benefits Related to AM

AM comes with several benefits according to previous literature. There is increased design freedom when designing parts for AM compared to CM (Thompson et al., 2016). Parts can be designed with increased functionality (Ford & Despeissie, 2016; Oettmeier & Hofmann, 2016; Thompson et al., 2016; Mellor et al., 2014). As more complex internal designs are possible with AM (Thompson et al., 2016). Thus, offering parts of increased quality (Chekurov et al., 2018). There is also the possibility to reduce the number of components with AM (Oettmeier & Hofmann, 2016). By printing one component instead of having to e.g., use lathering to join parts together. Thus, another AM design benefit is the possibility to reduce the number of joints (Chekurov et al., 2018). This is, however, only possible for components that are not limited by the chamber size of the machine. Moreover, parts can also be designed to be lighter in weight compared to CM methods (Javaid et al., 2021; Ford & Despeissie, 2016; Mellor et al., 2014).

AM is a flexible production method compared to CM options (Araújo et al., 2021; Togwe et al., 2019; Kretzschmar et al., 2018a), due to the AM machine being versatile (Oettmeier & Hofmann, 2016). Thus, reducing manufacturers' need for tooling (Holmström et al., 2010) and providing agility in the production (Gupta et al., 2020). The agility in production allows for customization (Thompson et al., 2016). I.e., producing small batches becomes possible (Mellor et al., 2014). Previous research states that small batches become economical with AM (Oettmeier & Hofmann, 2016; Holmström et al., 2010). The AM process is also said to require less manual labor in production compared to CM (Togwe et al., 2019). Thus, reducing the need for labor in production which can decrease costs associated with production (Togwe et al., 2019; Gebler et al., 2014). Similarly, Kretzschmar et al. (2018b) mean that operational costs are reduced by adopting AM technology.

Previous research also indicates that the AM can be faster than CM, thus reducing lead time s (Gupta et al., 2020; Kretzschmar et al., 2018b). The reduced lead time can allow manufacturers to adopt a just-in-time strategy (Ballardini et al., 2018). Or as others have referred to it, AM can lead to an on-demand production (Kretzschmar et al., 2018a; Peng et al., 2018; Holmström & Gutowski, 2017; Holmström et al., 2010). On-demand means that inventory would no longer be needed. In previous research, the most common consensus seems to be regarding AMs' possibility to reduce or eliminate physical inventory (Javaid et al., 2021; Togwe et al., 2019; Holmström & Gutowski, 2017; Thompson et al., 2016; Holmström et al., 2010). Inventory

reduction can lead to cost savings as well as reduced risk for the inventory holder (Togwe et al., 2019).

Apart from cost- and lead time -savings in the production process, AM also provides sustainability benefits according to previous literature. Due to the layer-by-layer technology AM allows for material waste reduction in the production process (Arjaúro et al., 2021; Javaid et al., 2021; Gupta et al., 2020; Wang et al., 2019a; Holmström & Gutowski, 2017; Ford & Despeissie, 2016; Gebler et al., 2014; Holmström et al., 2010). Naturally, reduced material consumption also affects the costs of production. In comparison to CM methods AM is also said to reduce energy consumption (Javaid et al., 2021; Gebler et al., 2014) and emissions (Gebler et al., 2014). Additionally, Javaid et al. (2021) mean that there is a possibility to reuse material by using AM. As the product can be recycled into powder which is the input material in some AM processes.

The AM technology compared to CM is said to require fewer suppliers of raw materials (Gupta et al., 2020; Oettmeier & Hofmann, 2016). I.e., solving or diminishing the multi-tier supply chain problem (Gupta et al., 2020). The combination of reduced steps downstream and the reduced steps required in production can provide a shorter supply chain with the use of AM compared to CM methods (Gupta et al., 2020; Mellor et al., 2014; Holmström et al., 2010). Thus, possibly reducing the supply chain complexity, and reducing overall lead times.

2.4.2 Benefits Related to AM-enabled Systems

With cloud-based AM Wang et al. (2019a) identified that a benefit may be diminished development time of parts by connecting experts and non-experts on the cloud-based platform. Ballardini et al. (2018) found that virtual libraries can improve companies' availability of parts, centralize the product data and thus make data more accessible, as well as facilitate the purchasing process. Regarding DIs Araújo et al. (2021), found that through AM DIs can be created, and thus the introduction of DIs can reduce physical inventories. Similarly, Chekurov et al. (2018) and Kretzschmar et al (2018a), found that DSP can reduce physical inventories. Moreover, an alluring benefit of both DI and DSPs that adopts a distributed approach is the possibility of moving the manufacturing closer to the point of consumption (Araújo et al., 2021; Chekurov et al., 2018). Being closer to the point of consumption would significantly lower transportation lead times and costs (Chekurov et al., 2018).

2.5 Challenges Related to AM & AM-enabled Systems

Previous literature exploring the challenges of DI is scarce and a limited amount of previous literature explicitly explores challenges from a centralized approach. To build the theoretical knowledge necessary to analyze our findings in Chapter 5 we have summarized literature covering challenges related to AM and AM-enabled systems from various manufacturing approaches in the sections below. The two have been divided as AM is a production method whereas an AM-enabled system, is a system enabled by the production technique. For example, Ballardini et al. (2018) identified IP rights as a challenge to virtual libraries as they are of a public nature. It is a challenge concerning the AM-enabled system, this challenge does not exist with AM alone as AM is merely a production method.

Additionally, to provide the reader with further clarity, the challenges derived from previous literature have been summarized and presented in Table 3 below. Along with a brief description of each study, what the challenges concern, and the stated manufacturing approach.

Table 3. Challenges Derived from Previous literature

Authors	Description of study	Challenges	Challenges Concern	Manufacturing Approach
(Holmström et al., 2010)	Conceptually compares centralized and decentralized AM spare-parts manufacturing	<ul style="list-style-type: none"> Cannot guarantee quality of parts Inventory cost vs. Capacity utilization 	AM	Centralized and decentralized
(Mellor et al., 2014)	Explored an implementation framework for AM	<ul style="list-style-type: none"> Post-processing adds environmental footprint Post-processing hinders decentralization 	AM	Centralized
(Thompson et al., 2016)	Identifies constraints, considerations and opportunities when designing parts for AM	<ul style="list-style-type: none"> High quality CAD models Post-processing necessity Machine capabilities (e.g., size limitations) Certification and approval process of designs Variability in output product Costly raw materials Costly machinery 	AM	N/A
(Ford & Despesse, 2016)	Explores public data to identify advantages and challenges related to AM and sustainability	<ul style="list-style-type: none"> Speed of AM production Certification of new components Uncertain performance of the AM process 	AM	Not considered
(Knofius et al., 2016)	Suggested a methodology for identifying spare-parts appropriate for AM production	<ul style="list-style-type: none"> Availability and quality of product data varies 	AM	N/A
(Li et al., 2017)	Theoretically compares conventional production to centralized AM and distributed AM	<ul style="list-style-type: none"> AM is expensive (mainly cost of machine) 	AM	Centralized and distributed
(Tofail et al., 2018)	Identifies scientific and technological challenges with AM as well as market uptake and opportunities	<ul style="list-style-type: none"> Post-processing necessity 	AM	Not considered
(Ballardini et al., 2018)	Conceptually explores AM-enabled publicly available virtual libraries related challenges	<ul style="list-style-type: none"> IP rights Lack of harmonization in the EU legal framework Non-digitalized component & product information Outsourcing parts of the production Resistance to change 	Virtual libraries	Not considered
		<ul style="list-style-type: none"> Costly production method Costly raw materials 	AM	
(Kretschmar et al., 2018a)	Evaluating the readiness of AM DSP	<ul style="list-style-type: none"> Low no. of usable materials Insufficient accuracy levels & tolerances Size limitations Post-processing necessity 	AM	Not considered
(Chekurov et al., 2018)	Conceptually explores benefits of AM DSP	<ul style="list-style-type: none"> Current ICT infrastructure 	DSP	Distributed
		<ul style="list-style-type: none"> Post-processing necessity 	AM	
(Peng et al., 2018)	Discusses AM energy consumption and environmental impact	<ul style="list-style-type: none"> Post-processing hinders decentralization Lack of lifecycle assessments 	AM	N/A
(Abdulhameed et al., 2019)	Reviews trends, challenges, and applications of the AM technology	<ul style="list-style-type: none"> Deconstructed parts due to size limitations 	AM	N/A
(Frandsen et al., 2020)	Literature review on AM, spare-parts, and selection methods	<ul style="list-style-type: none"> Understanding characteristics of parts suitable for AM Selection method for parts suitable for AM 	AM	N/A
(Chekurov et al., 2021)	Conceptually explores adoption barriers of AM DSP	<ul style="list-style-type: none"> Lack of knowledge about the AM technology Distrust in AM's output quality Costly production method Speed of AM production 	AM	Distributed
		<ul style="list-style-type: none"> IP rights Regulatory issues Resistance to change 	DSP	
This research will...	Conceptually explore challenges related to AM-enabled DI	<ul style="list-style-type: none"> See findings & analysis for the challenges we identified 	DI	Centralized

2.5.1 Challenges Related to AM

Before any design or production can commence, one must understand what to produce with AM. A limited amount of literature has yet been devoted to understanding what characteristics of parts are suitable for AM (Frandsen et al., 2020). In addition, Knofius et al. (2016) found that there is a lack of availability and quality of product data. Product data is necessary to better understand the characteristics of the component to determine what to produce with AM once a selection method for parts suitable for AM has been established. A limited amount of previous literature has focused on identifying an appropriate selection method thus far (Frandsen et al., 2020). Hence, before the design or production commences, some challenges have already been identified.

When designing for AM several constraints need to be taken into consideration (Thompson et al., 2016). The CAD model needs to be of high quality to be printable which is different from CM methods. Depending on the AM machine at hand, the chamber size of the AM machine may also pose size limitations to the designs (Kretschmar et al., 2018a; Thompson et al., 2016). Due to the size limitation, parts may have to be deconstructed into smaller pieces which can pose a design challenge as the pieces then have to be joined together at a later stage (Abdulhameed et al., 2019).

After producing a design, the certification and approval process of the new design poses a challenge (Thompson et al., 2016; Ford & Despesse, 2016). The certification process can be time-consuming and costly. To certify a new design, the design must go through the entire production process to make sure the new design meets various criteria. Even if a design has been certified once, issues to the design might still occur after the printing has been conducted. The AM process is still considered a rather immature process and the lack of knowledge about the AM process causes challenges for manufacturers (Chekurov et al., 2021). Due to this lack of knowledge among other things, variability in the product output occurs (Thompson et al., 2016). I.e., the uncertain performance of the AM process poses a challenge (Ford & Despesse, 2016). Thus, guaranteeing the quality of parts may pose a challenge to manufacturers (Holmström et al., 2010). The sensitivity of the AM machine poses challenges that can result in insufficient accuracy levels and tolerances (Kretschmar et al., 2018a). The sensitivity of the AM process makes it sensitive to changes in material input as it may affect the quality of the

part produced. This naturally leads to a distrust in the quality of parts produced with AM (Chekurov et al., 2021). Due to the sensitivity to changes in material composition, the material needs to be considered already in the design stage (Thompson et al., 2016). There is a low number of usable materials (Kretschmar et al., 2018a), and the materials used are costly (Ballardini et al., 2018; Thompson et al., 2016). Apart from the material, the acquisition cost for the machinery is also steep (Li et al., 2017; Thompson et al., 2016). Overall, AM is currently a rather costly production method (Chekurov et al., 2021; Ballardini et al., 2018; Li et al., 2017). Moreover, Holmström et al. (2010) mean that another cost-related challenge with AM is reducing the inventory cost while maintaining a good capacity utilization to remain profitable.

Many might believe that AM is simply pressing a button and out comes a finished product, however, this is not the case. AM production generally requires post-processing (Chekurov et al., 2018; Kretschmar et al., 2018a; Tofail et al., 2018; Thompson et al., 2016). Post-processing may involve coating, heat treatments, etc. I.e., CM methods. The post-processing necessity is brought up as a challenge in previous literature. Additionally, parts of AM production are often outsourced (Ballardini et al., 2018). Whether the outsourced parts are the AM process itself or its following post-processing steps, outsourcing parts of the production adds complexity to any supply chain and reduces the manufacturer's control. Thus, outsourcing is viewed as a challenge in previous literature. Another challenge mentioned in previous literature regarding the AM process is that the speed of production is rather slow (Chekurov et al., 2021; Ford & Despesse, 2016). However, previous literature does not state if the printing process is slow, or if the slow speed refers to the printing process plus the necessary post-processing. Nor does previous literature explain in comparison to what the AM process is considered slow.

Previous literature could be considered somewhat contradictory regarding the impacts AM has on sustainability. In the benefits section of this chapter, we highlighted the benefits regarding AM and sustainability. However, previous literature also implies that AM faces environmental sustainability challenges. The post-processing necessity adds to the environmental footprint of using AM (Mellor et al., 2014). The post-processing necessity may also hinder a full decentralization of AM, which could otherwise offer significant reductions to energy consumption in distribution, given that the unprocessed material requires less space (Peng et al., 2018; Mellor et al., 2014). Moreover, Peng et al. (2018) mean that a limited amount of literature has explored AM's energy consumption and environmental impact from a life cycle assessment perspective, hindering definitive statements on AM's environmental impact.

2.5.2 Challenges Related to AM-enabled Systems

Previous literature has identified IP rights and regulatory challenges concerning both publicly available virtual libraries and distributed DSP (Chekurov et al., 2021; Ballardini et al., 2018). Patent laws have previously mainly protected physical goods, sharing a CAD model thus becomes worrisome for the CAD designer (Ballardini et al., 2018). The regulatory framework regarding patent rights may also differ between countries, posing a challenge in a digitalized world. Additionally, both virtual libraries and DSP requires a shift in CM as well as a shift in inventory management. Manufacturing industries have been described as conservative, thus previous literature has found that resistance to change is a challenge for both AM as well as virtual libraries and DSP (Chekurov et al., 2021; Ballardini et al., 2018). Both individual and organizational resistance has been identified. Chekurov et al. (2021), mean that the individual resistance stems from a distrust in AM and reluctance to learn new technologies. While the organizational resistance stems from a reluctance to commit to the magnitude of change initiatives. Regarding virtual libraries, Ballardini et al. (2018) found that the currently non-digitalized components and product information is a challenge for companies. While Chekurov et al. (2018) found that current ICT infrastructures might not conform to the changes necessary to develop a DSP network. Thus, costly investments in ICT might become necessary.

2.6 Normann's Model

The choice to apply Normann's model in this research was to give the reader a further understanding of the DI concept along with discovering the potential value which may be drawn from the implementation of DI. Although it is not customary to use frameworks in this way within this field, we believe that it can enhance the reader's understanding of why researchers and companies explore the DI concept. This model will later be applied in Chapter 5.

With new technology comes the opportunity to reconfigure business activities (Normann, 2001). Reconfiguration can affect the **density**, one of the principles in Normann's model as shown in Figure 2. Normann's model in relation to technology relieves us of the restrictions of the specific actor, the time, the place, and the constellation. Furthermore, density means that "The best combination of resources (that) is mobilized for a particular situation – e.g., for a customer at a given time in a given place – independent of location, to create the optimal value/cost result" (Normann, 2001, p.27). In other words, according to Normann's model,

density is perceived as the degree to which such resources can be accumulated for an actor or specific space.

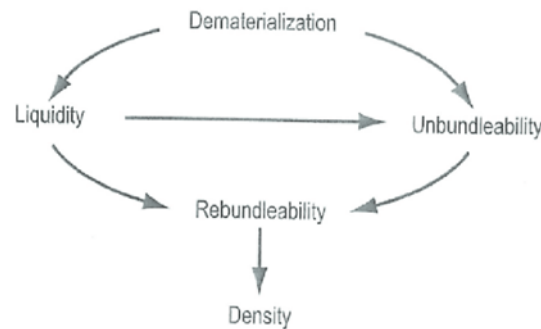


Figure 2. Drivers Promoting Density (Normann, 2001, p.30).

Normann's model of promoting density and reconfiguration can be explained as followed. The first principle talked about in Normann's model is **Dematerialization** which refers to the removal of physical attributes in favor of the non-physical, e.g., digitization (Normann, 2001). When information has become dematerialized, it becomes **liquid** – easier to move about. Thus, liquification is a consequence of the separation from the physical world. Electronic communication is an example of materialized and liquid information (Michel et al., 2007). In turn, a consequence of dematerialization and liquification is the principle of **unbundle-ability** (Normann, 2001). Unbundle-ability refers to the separation activities that hitherto have been “well defined and held together in time and place by actor” (Normann, 2001, p.33). Following the principles of dematerialization, liquification, and unbundle-ability, digitalization can also promote **re-bundle-ability** (Normann, 2001). Meaning that activities and assets can be put together again. Putting together activities or assets at a desired place or time is what can promote density. Thus, changing how value can be created. Through digitalization, Normann suggests that organizations shift focus from product offerings to a value creation process (Michel et al., 2007).

3. Methodology & Method

In this section, the reader is introduced to the methodology and method used in this research. The methodology section contains the research philosophy, the research approach, and the research design. In the methods section, the data collection and data analysis are explained, and the trustworthiness and ethical considerations are presented.

3.1 Methodology

3.1.1 Research Philosophy

The research philosophy in general means “the development of knowledge and the nature of that knowledge” (Saunders et al., 2007, p. 107), it is what guides how the research is being conducted. To describe this the ontological and epistemological stance is often stated and motivated. The ontological position describes how the researchers view reality (Easterby-Smith et al., 2018), and answers the question ‘what is reality?’ (Byrne, 2017). The epistemological position describes the researchers’ assumption about how to inquire that knowledge (Easterby-Smith et al., 2018), by answering the question ‘how can we know reality?’ (Byrne, 2017). For the methodology of this research, our MRQ is the guiding research question.

In this research, the ontological position adopted is called **relativism**. Implying that we perceive reality as subjective as it depends on the perspectives from which we observe them (Easterby-Smith et al., 2018). I.e., there are several truths that depend on the viewpoint of the observer. This position is necessary to answer our research questions, as it allows us to collect data from various industry experts to identify benefits and challenges related to DI from various perceptions. This is important as an e.g., logistician may envision some challenges that engineers do not see and vice versa, due to the different professional backgrounds and areas of expertise. To not add our own bias to this research we do not perceive viewpoints as more or less important.

The relativist position’s denial of a universal truth (Given, 2008) is necessary as the case company currently does not have a DI. Thus, potential benefits and challenges cannot be directly accessed, and a single truth cannot be found or considered concrete. Following this reasoning, it also becomes evident why the ontological positions of realism and internal realism are not appropriate for this research. As realism implies that “facts exist and can be revealed”

(Easterby-Smith et al., 2018, p.118), while internal realism implies that “facts are concrete, but cannot be accessed directly” (Easterby-Smith et al., 2018, p.118). Nominalism on the other hand implies that “there is no truth... facts are all human creations” (Easterby-Smith et al., 2018, p.118). This does not hold true for the sake of this research as our MRQ entails identifying several perspectives of the truth.

Following the relativist ontology, we adopted a **constructionist** epistemology. This means that we obtain knowledge through multiple specifically chosen people sharing their experiences and expertise through words (Easterby-Smith et al., 2018). Inquiring knowledge from multiple people is necessary due to the aim of our MRQ and ontological position. Furthermore, this epistemological position aims to increase general understanding, in line with our purpose. As the idea is that a general understanding of benefits and challenges related to a DI can help navigate how to best use AM. The positivistic epistemological positions, which are often connected to realism and internal realism, assume that properties can be measured through objective methods (Easterby-Smith et al., 2018). As the case company currently does not have a DI, we cannot inquire knowledge through objective methods.

3.1.2 Research Approach

The research approach describes how the theory will be used; deductively, inductively (Saunders et al., 2007), or abductively (Given, 2008). Deductive research is about testing a theory, moving from theory to data (Saunders et al., 2007). If the premises of deductive research are correct, the conclusion can be considered certain (Given, 2008). Inductive research is about theory generation through empirical data findings (Saunders et al., 2007), and conclusions drawn can be considered probable (Given, 2008). Abductive research draws upon the weaknesses of deduction and induction. It is about explaining to understand people, events, etc. (Mills et al., 2010), and conclusions drawn can be considered plausible (Given, 2008). The different approaches can also be used in combination (Saunders et al., 2007).

This research is mainly **inductive** as we aim to inductively explore emerging patterns from the data collected, to develop theoretical knowledge on the DI concept. However, as for most research deductive elements do occur, and are visible in Chapter 5. Overall, we reason from particular to general, in line with inductive research (Salkind, 2010). The inductive approach's appropriateness can be revealed logically in our research. 1). Following the research question and research philosophy, this research follows a qualitative approach. Qualitative research is often linked to inductive research (Salkind, 2010). 2). Our purpose is of an **exploratory** nature.

Exploratory research is often connected to inductive research (Stebbins, 2001). Additionally, contributing to the theoretical knowledge in an inductive and exploratory way has been conducted in a similar manner in this field in previous research, e.g., Chekurov et al. (2018) inductively explored the perceived added value of DSP.

Furthermore, as we identified gaps in the literature regarding how DI is described and perceived benefits and challenges related to DI, we cannot hold previous assumptions that would be tested. Nor could we conduct actual testing as the case company currently does not have a DI. Thus, purely deductive research would not be appropriate to conduct. Moreover, for the intent and structure of this thesis, an inherently abductive approach would not suffice to reach the intended research intent. An abductive approach is according to Mills et al. (2010) related to the element of surprise in research to generate new theories. Seeing as this is neither the aim nor structure of the research, abduction was deemed unfit for this paper.

3.1.3 Research Design

This research follows a qualitative research design considered appropriate given our research philosophy (Easterby-Smith et al., 2018), and our MRQ. Qualitative research focuses on developing an understanding of things often expressed in terms of language, as opposed to quantitative research which often focuses on generating hard facts in terms of numerical data (Easterby-Smith et al., 2018).

We adopted a **single case study** design. Meaning that we focus in-depth on a single organization (Easterby-Smith et al., 2018). The single case approach is suitable given our MRQ, where we focus on collecting the perspectives from industrial practitioners in a large manufacturing organization and given our constructionist epistemology. In constructionist case study research, the goal is to contribute to a theoretical discourse (Given, 2008), and involve sampling from multiple individuals within a single-case (Easterby-Smith et al., 2018).

The in-depth focus of case study research provides a rich understanding of the context (Saunders et al., 2007), necessary in this research to obtain benefits and challenges from various perspectives. Additionally, case study designs are often used in exploratory research (Saunders et al., 2007). We focused on a single case due to the access to a unique environment. A manufacturing organization utilizing metal AM in spare part production, allowing us to

conceptually research the new DI concept. Gaining access to multiple cases using AM within the same context was deemed unlikely. Considering the high confidentiality involving emerging technologies. As AM developments are regarded as a competitive advantage. Lastly, a common critique of single case research is its perceived lack of generalizability (Easterby-Smith et al., 2018), however, we intend to be transparent and clear about our context to diminish these critiques.

3.2 Method

3.2.1 Data Collection

The data collection was conducted at two separate stages of the research and in two different ways. To provide clarity for the reader we will explain the data collection and method of sampling conducted for our SRQ and MRQ separately. Starting with the SRQ to provide a logical order for the reader. Since the SRQ set the context for the MRQ, we began the data collection for MRQ when the findings for the SRQ had been analyzed.

3.2.1.1 Primary Data

Previous literature does not describe a DI, nor does it explore perceived benefits and challenges. Therefore, new data was needed, i.e., primary data (Easterby-Smith et al., 2018). Primary data allowed us to collect specific and relevant data necessary to answer both research questions. The research questions are of a qualitative nature, hence appropriate collection methods include but are not limited to, observations, focus groups, interviews (Smith & Bowers-Brown, 2010), and group interviews (Easterby-Smith et al., 2018). In this research, we will use interviews to gather data for SRQ, and group interviews to gather data for MRQ. Each collection method will be explained more in detail below.

3.2.1.1.1 Primary Data SRQ

For the SRQ, qualitative interviews were chosen as the method for data collection, since it allows for rich and detailed data to be collected (Easterby-Smith et al., 2018). The interviews were in-depth and semi-structured, and probes were used to allow for more information to emerge (Smith & Bowers-Brown, 2010). The interview guide used for SRQ is available in Appendix 1. In-depth and semi-structured interviews are a good complement to exploratory research and can be used to gather new insights and give a rich view of the general context in which one is making research (Saunders et al., 2007). Semi-structured interviews are often

used in exploratory research to find and understand the connection between different variables within the research.

All respondents were contacted via email, often an initial email was sent by the respondent who made the referral to create trust. The interview questions were shared in advance to allow the respondents to prepare for the interview and think about the questions to provide deeper answers. The virtual interviews were held over Zoom using the video function. At the beginning of the data collection for SRQ Covid-19 restrictions hindered the otherwise preferred face-to-face option. To provide all respondents with the same circumstances the remote interviews were kept throughout the collection process of SRQ despite the relief in restrictions. Moreover, all interviews were audio recorded with the approval of the respondents and later transcribed. The interviews were held in Swedish as the respondents felt more comfortable expressing themselves more precisely in their native language. Citations used have thus been translated. Information about each interview and respondent can be found in Table 4.

Table 4. *Information about the interviews for SRQ*

Respondent	Department	Date	Duration
A	R&D - Technology & Innovation	27/1-22	26 min
B	R&D – Industrialization & Digitalization	28/1-22	40 min
C	IT	28/1-22	24 min
D	Production	28/1-22	18 min
E	R&D - Technology & Innovation	31/1-22	31 min
F	R&D - Technology & Innovation	8/2-22	47 min
G	Logistics	10/2-22	37 min
H	Sales	21/2-22	40 min
Total Duration			236 min

3.2.1.1.2 Primary Data MRQ

For MRQ, **group interviews** were chosen as the primary data collection method. Group interviews refer to interviews where two or more people are being interviewed (Saunders et al., 2007). Generally, a smaller group is suitable for complex subjects (Saunders et al., 2007), and can be beneficial to counteract social pressures e.g., fear of public speaking (Easterby-Smith et al., 2018). In this research, each interview session was comprised of two respondents and two researchers. The small group number is also more probable to allow for the gathering of in-depth information (Saunders et al., 2007). Additionally, a common critique of group interviews

is that it may result in some participants not being able to get their point across due to some being more vocal than others. This risk was however eliminated with the choice of doing small group interviews with only two participants in each. The conceptual understanding of what a DI is, as identified through our SRQ, was sent out before the group interviews to allow the respondents to get familiarized with and start thinking about the concept. The description that was sent out is available in Appendix 2.

Moreover, a semi-structured interview format was applied, and probes were used for the same reasons as described in the SRQ section. The interview guide used can be found in Appendix 3. We preferred the group format over individual interviews as we expected that the group format would encourage individuals to think about benefits and challenges that they might otherwise not have thought about, by hearing the thoughts of another individual. Group interviewing is considered appropriate when the topic concerns questions of a relatively unfamiliar nature (Gaskell, 2000), as in the case of our chosen topic. The group interview format also allowed us to collect data from a larger group of respondents in a time-efficient manner. Which is one purpose of conducting group interview research (Bloor & Wood, 2006), and providing us with a range of opinions (Gaskell, 2000). Another purpose of group interviews is to gain access to respondents' individual opinions (Bloor & Wood, 2006). Given our philosophical position, this was something we aimed for as we accept that there are multiple truths dependent on the viewpoint of the observer. This also shows a clear distinction between group interviews and focus group research, as focus group data collection is instead concerned with how respondents discuss something (Bloor & Wood, 2006). With that said we did, however, not hinder naturally occurring discussions between respondents.

We held 10 group interviews, meaning that 20 respondents were interviewed, and each interview lasted around 60 minutes. When forming the groups, the different hierarchical statuses of the respondents were necessary to consider, to prevent fear of speaking (Easterby-Smith et al., 2018). Thus, all groups consist of respondents with similar statuses. The statuses will however not be revealed to protect the anonymity of the respondents. To determine the respondents' status, we looked at an organizational chart. Information about each group interview and the respondents can be found below in Table 5. Given our philosophical position, where we gain access to the several truths through respondents with different perspectives, we deemed it relevant to include the respondents' department belonging. Due to scheduling clashes and respondents' voluntary participation, all group interviews were not constructed in the same

way regarding department belonging. Instead, we focused on homogeneity in hierarchical status. Additionally, all respondents worked within the AM part of the same company. This homogeneity is expected to provide a safe environment for information considered sensitive in group interviewing formats (Liamputtong, 2011a).

An invitation for the group interview was sent out via email. All group interviews were held virtually, using the video function in Teams. This was chosen to be able to facilitate the group interviews in a similar manner throughout and include respondents who were still working from home. When adopting virtual interviews, it is important to consider the respondents' familiarity with the format (Easterby-Smith et al., 2018). We considered the virtual format appropriate as the case company has been holding all meetings virtually during the past few years due to Covid-19. We switched from Zoom to Teams as we found out during the SRQ interviews that the respondents were more familiar with Teams. Moreover, virtual group interviewing formats may reduce respondents' inhibitions (Liamputtong, 2011b). With the respondents' permission, the sessions were audio-recorded to later enable transcription. All sessions were held in Swedish. Thus, quotes used in this research have been translated.

Table 5. *Information about the group interviews for MRQ*

Group	Respondent	Department	Date	Duration
A	1	R&D – Innovation & Technology	21/3-22	60 min
	2	R&D – Innovation & Technology		
B	3	R&D – Medium Gas Turbines	21/3-22	58 min
	4	R&D – Medium Gas Turbines		
C	5	Logistics	23/3-22	58 min
	6	Logistic		
D	7	Production	23/3-22	57 min
	8	Order Management		
E	9	Production	23/3-22	60 min
	10	Design		
F	11	R&D - Industrialization & Digitalization	24/3-22	58min
	12	R&D – Technology & Innovation		
G	13	Engineering	25/3-22	61min
	14	Order Management		
H	15	IT	25/3-22	70 min
	16	R&D - Technology & Innovation		
I	17	Operations	28/3-22	60 min
	18	Logistics		
J	19	Operations	30/3	60 min
	20	Operations		
Total Duration				602 min

3.2.1.2 Sampling Strategy

As this research is qualitative, non-probability sampling designs have been used (Easterby-Smith et al., 2018). However as previously established, this research was conducted in two steps, and two different sampling designs have been used; both will be explained separately below.

3.2.1.2.1 Sampling Strategy for SRQ

For the SRQ, a snowball sampling design was used. This means that the initial respondent who was selected based on a set criterion was asked after the interview to give suggestions to other eligible candidates for the research purpose (Easterby-Smith et al., 2018; Lewis-Beck et al., 2004). The first referral was made by our supervisor at Siemens Energy. The inclusion criterion was that the respondent must have worked with the case company's current AM practices. This criterion is expected to help in identifying individuals who hold insights valuable for answering the SRQ. The snowball sampling design was appropriate to locate eligible respondents who may be located outside of the realm of recollection of the supervisor (Easterby-Smith et al., 2018). Snowball sampling design may be used to access potential candidates in networks within the organization. Furthermore, this sampling design is particularly useful when the research regards matters that are confidential as the referrals create trust (Easterby-Smith et al., 2018; Lewis-Beck et al., 2004). The AM segment at the case company is at a development stage and is considered to hold promising competitive advantages, thus the case company considers topics regarding AM as highly sensitive. We stopped the sampling once no new referrals were made. Following the set criterion, 8 respondents were included.

3.2.1.2.2 Sampling Strategy for MRQ

For the MRQ, a purposive sampling design was used. Similarly, to snowball sampling, respondents must meet a criterion for inclusion (Easterby-Smith et al., 2018). However, the purposive sampling design differs in that it does not identify candidates based on referrals. Given that we had already established trust and gotten to know the company better – through interviews and company visits, referrals were no longer deemed necessary. We developed new criteria for inclusion. The new criteria for inclusion were that the respondent must have worked with the case company's current AM practices and belong to one of the following departments: Research & Development, Operations, Order Management, Engineering, Design, Production, IT, or Logistics.

The departments necessary to include were based on departments that would be affected by the implementation of a DI according to the respondents interviewed for SRQ. Furthermore, we considered the inclusion of various departments appropriate as we have a constructionism epistemology and expected that respondents with different backgrounds would add different perspectives necessary to answer the MRQ. Moreover, with purposive sampling, the objective is to “produce a sample that can be logically assumed to be representative of the population” (Lavrakas, 2008, p.2). This is yet another reason for adopting the department criterion, to capture as many perspectives from the AM segment of the organization as possible.

3.2.2 Data Analysis

Even though the data collection and analysis for SRQ and MRQ occurred on two separate occasions, the analysis conducted to analyze the data was conducted in the same way. Thus, we will only explain the data analysis once. However, specific explanations for decisions made for SRQ and MRQ will be described. When conducting the data analysis for MRQ, we did the analysis twice – once to identify benefits, and once to identify challenges.

In this research, we conducted an **inductive thematic analysis**. Thematic analysis is suitable for constructionist designs (Braun & Clarke, 2006), and when analyzing interview data (King & Brooks, 2018). We aimed to conduct a within-case analysis of the data, looking in-depth at a single organization (Mills et al., 2010). Although all data collected was analyzed, only parts of the data will be presented, as qualitative research often produces large amounts of data (Tight, 2017a). Thematic analysis seeks to identify and make sense of rich data sets, by identifying patterns or themes, to allow the reader to understand important aspects of the research topic (King & Brooks, 2018; Braun & Clarke, 2006). The thematic analysis approach allows for both deductive and inductive approaches to theme identification (Braun & Clarke, 2006). In this research, we conducted an inductive approach to thematic analysis, meaning that the themes emerged from the data. The inductiveness of the analysis was suitable given our exploratory purpose and the scarcity of previous literature describing DI and related perceived benefits and challenges.

Most qualitative methods use thematic analysis to derive meaning from data (King & Brooks, 2018). Some researchers prefer to view thematic analysis as an umbrella term for various analysis approaches, but some argue that it should be considered its own data analysis approach

(Braun & Clarke, 2006). Thematic analysis is a popular approach to analyzing qualitative data (Tight, 2017b). However, thematic analysis is often criticized for its flexible approach how to step-by-step analyze the data, making it difficult to replicate (Mills et al., 2010). To counteract this, we followed the well-known steps suggested by Braun and Clarke (2006) and explained each step both in text and visual form. The visualization of how the data analysis was conducted for SRQ is available in Appendix 4, and Appendix 5 and 6 for MRQ benefits and challenges.

3.2.2.1 Step 1: Familiarizing Yourself with your Data

After the collection of primary data, the data had to be transcribed into written form to allow for thematic analysis (Braun & Clarke, 2006). Since transcribing can be time-consuming, we divided the transcription equally between us. During the transcription, we began to familiarize ourselves with the data. We also read over all the transcripts individually to get further familiarized.

3.2.2.2 Step 2: Generating Initial Codes

Once the familiarization stage was done, the initial coding process began (Braun & Clarke, 2006). First, we coded individually to adopt an investigator triangulation approach as described by Guba (1981). We then compared our initial codes and agreed on codes that were aligning. For SRQ 11 codes were agreed upon. For MRQ benefits, 15 initial codes were agreed upon, and for challenges, 24 codes were agreed upon. Minor alterations to the codes had to be made to fully align our individual codes with one another, the meaning of the codes did, however, not change. Throughout the coding process, we kept our research question/s in mind.

3.2.2.3 Step 3: Searching for Themes

Once the initial codes were done, we began analyzing the codes to identify patterns/themes (Braun & Clarke, 2006). This was done by looking at the already existing pool of codes from the previous step and compiling them into different themes based on coherence between the codes. A total number of 3 themes could be agreed upon for SRQ. For MRQ benefits, 5 themes were agreed upon and for challenges, a total number of 6 themes were agreed upon for MRQ challenges.

3.2.2.4 Step 4: Reviewing Themes

The step was to review the different themes from the previous step (Braun & Clarke, 2006). In the review process, each theme was examined to determine whether the themes held up on their own or needed to be connected to other themes or removed altogether. In this step of the analysis

process, to refine the collection of themes we looked at the constructed themes and examined each pattern and its cohesiveness.

For SRQ the initial 3 themes were reviewed and changed to 4 themes. The initial “information” theme was split into “information storage”, “simplified information sharing”, and “information protection”. The division was done to illustrate the original codes more precisely and provide a detailed depiction of the overarching meaning behind our codes. Additionally, the theme “One-stop” and “production planning visibility” merged under the name “One-stop,” as we realized production planning visibility was a part of the one-stop function. Lastly, after careful evaluation, the previously discovered code “payment service” which belonged to “one-stop” was removed from the data sets entirely.

For MRQ benefits the initial 5 themes were reviewed and changed to 4 themes. The initial themes “Shortened information flow” and “Process Optimization” were merged into one, as shortened information flow is a type of process optimization. The codes “digitalization can reduce manual steps,” “reduced manual labor in order management”, and “easier to place orders” were merged into one code. The new code was called “reduced manual steps.” The code “easier to access information” was moved as we realized that this was a result of the “centralized data.” Additionally, the initial codes “reduced lead time s” and “AM is faster than CM” were merged into one code. The new code was “reduced lead time s.” After this step, we had 4 themes and 12 codes for MRQ benefits.

For MRQ challenges the initial 6 themes were reviewed and changed to 7 themes. The “operation issues” theme was divided into two to better capture the connected codes. The new theme was called “post-processing.” The code “post-processing adds lead time” was merged with “post-processing degrades the value of a DI” and given a new code to better capture the data extracts. The new code was “post-processing lead time degrades the value of a DI.” The code “fear of change” was removed as it expressed the same thing as “individual resistance to change.” Additionally, the code “AM is slow” was altered to “AM process too slow for DI” to better explain the context. After this step, we had 7 themes and 22 codes for MRQ Challenges.

3.2.2.5 Step 5: Defining & Naming Themes

In this step, we refined and defined our themes one last time to capture the essence of each theme and to establish final theme names as described by Braun and Clarke (2006). To do this, we had to revisit the data extracts. We aimed at having rather telling themes to enable the reader to get an instant sense of what the themes were about.

For SRQ, “One-stop” was renamed “One-stop order fulfillment,” to provide the reader with a better understanding of the theme and to encompass the previously merged theme. In a make-to-order scenario, fulfillment also entails the production, thus we saw this name as better describing the codes the theme covered. The other names of themes were kept as they were.

For MRQ benefits and challenges no changes to the theme names were made at this point as the themes were deemed descriptive enough for a reader to understand the essence of the benefit/ challenge. For MRQ challenges a code was however refined to “Export laws compliance.”

3.2.2.6 Step 6: Producing the Report

Once the themes had been finalized, the production of the report began. In thematic analysis, it is recommended to use data extracts to tell the comprehensive story of the data (Braun & Clarke, 2006). For both SRQ and MRQ, data extracts were used. The result of the thematic analysis is available in Chapter 4.

3.2.3 Research Quality

Constructionist designs are often questioned for their quality, especially by researchers from a positivistic position (Easterby-Smith et al., 2018). To evaluate the quality of this research, we undertook a well-known criterion for trustworthiness listed below.

3.2.3.1 Credibility

The credibility concerns the truth value of the research (Guba, 1981). We ensured that we included multiple perspectives through the department criterion. This helped us in reducing bias that might have occurred if including merely a single department. To minimize our own bias both researchers conducted the data collection and data analysis process, the initial coding step was however conducted separately. A way in which researchers can enhance credibility is by exposing thoughts about the research and incorporating feedback from others, I.e., peer-

debriefing (Guba, 1981). This research has continuously been subjected to peer debriefing and has incorporated feedback from the case SE supervisor weekly, the university supervisor monthly, seminar group members, as well as others with academic backgrounds. AM experts at SE were also consulted monthly and feedback was incorporated.

3.2.3.2 Transferability

The transferability concerns the applicability of the research to other cases (Guba, 1981). To determine the transferability or the degree of “fit,” it is important to provide descriptions of the research settings and method. Thus, we have provided detailed steps of our method, along with providing the reader with information regarding the data collection. A summary of the case company has also been provided to ensure that the reader is well versed in the context of the study. To allow the reader to determine the transferability to other cases.

3.2.3.3 Dependability

The dependability concerns the consistency of the research (Guba, 1981). Although, qualitative research with our connected philosophical position accepts multiple realities, both the stability of data and traceability of variable data needs to be taken under consideration. We aimed at enhancing the dependability by providing detailed steps of how the research was conducted to make sure that the reader will have rich insight into the different steps. Moreover, to ensure dependability and stability, the decision was made to initially code the data separately and then merge the joint findings. I.e., we adopted an investigator triangulation approach (Guba, 1981).

3.2.3.4 Confirmability

The confirmability concerns the researchers’ neutrality and objectivity (Guba, 1981). Given our acceptance of multiple realities, we are highly aware of issues concerning bias. To not let our own bias, affect the findings but rather let the data speak for itself, we have attempted to practice reflexivity. By presenting the reader with our underlying assumptions, and by critically reflecting upon codes, themes, etc. during the analysis process. During the data collection process, we avoided steering the respondents towards various topics as that could cause interview bias (Easterby-Smith et al., 2018). Probes were also asked to allow for deeper insights, but also clarification to avoid misunderstandings. Additionally, we perceived the constant feedback as useful for bias reduction.

3.2.4 Ethical Considerations

The ethical considerations related to conducting research are to be treated as a vital consideration for researchers (Saunders et al., 2007). Several ethical measures were used when

conducting this research. A non-disclosure agreement with the case company was signed before carrying out the study in which we promised to not disclose company sensitive information. This is to ensure no harm to the research subject organization or research participants. Saunders et al. (2007) bring up consent as another important ethical consideration for researchers. To ensure that the consent was captured for SRQ and MRQ the respondents were informed before the interview via email about the research questions and research intent. Additionally, we asked respondents for permission to record and use the recorded material for our analysis. The same measures of precautions were carried out ahead of the data collection for MRQ to ensure full consent from the participants. Respondents are anonymous as it was not necessary for the research intent to reveal any additional information, other than department belonging.

Considering that this research was carried out at the end of Covid-19 certain measures had to be taken to ensure the safety of the respondents and us as researchers (Newman et al., 2021). Interviews were therefore held virtually, and sufficient safety precautions were employed for company visits. Additionally, researchers must remain objective toward the research subject and data collected (Saunders et al., 2007). This means that we had to ensure that the data was collected fully, objectively, and without selectivity in the gathering process. Lastly, being objective to one's research is also an important consideration for the validity and reliability of the work.

4. Empirical Findings

In this section, the findings from the data collected will be presented. Firstly, the current ordering process of the case company is available to allow the reader familiarization with the case and a deeper understanding of the context. Secondly, the findings for the SRQ are presented, and lastly, the findings for the MRQ can be found.

4.1 The Current Ordering Process of Siemens Energy

To remind the reader of what type of company SE is a summary about SE is presented in Table 6. The table contains the same information as presented in Chapter 1.

Table 6. Information summary about the case company

Company Name	Siemens Energy
Industry	Energy
Type of Company	Manufacturing
Components	Spare-parts (turbine parts, and tools)
Material	Metal
AM technique	SLM

SE is currently using AM as a substitute for CM in their spare part supply chain, mainly for complex parts as a reduction in lead time and increase in quality has been observed through this shift. Despite the introduction of AM, SE still holds both planned and unplanned inventory, and thus operates with a make-to-stock strategy. Production occurs as per order and demand forecast basis. SE produces both prototypes and serial production components with AM. For components in serial production, a simplified process map is visible in Figure 3. For an explanation of the symbols used in the process map please see Appendix 7.

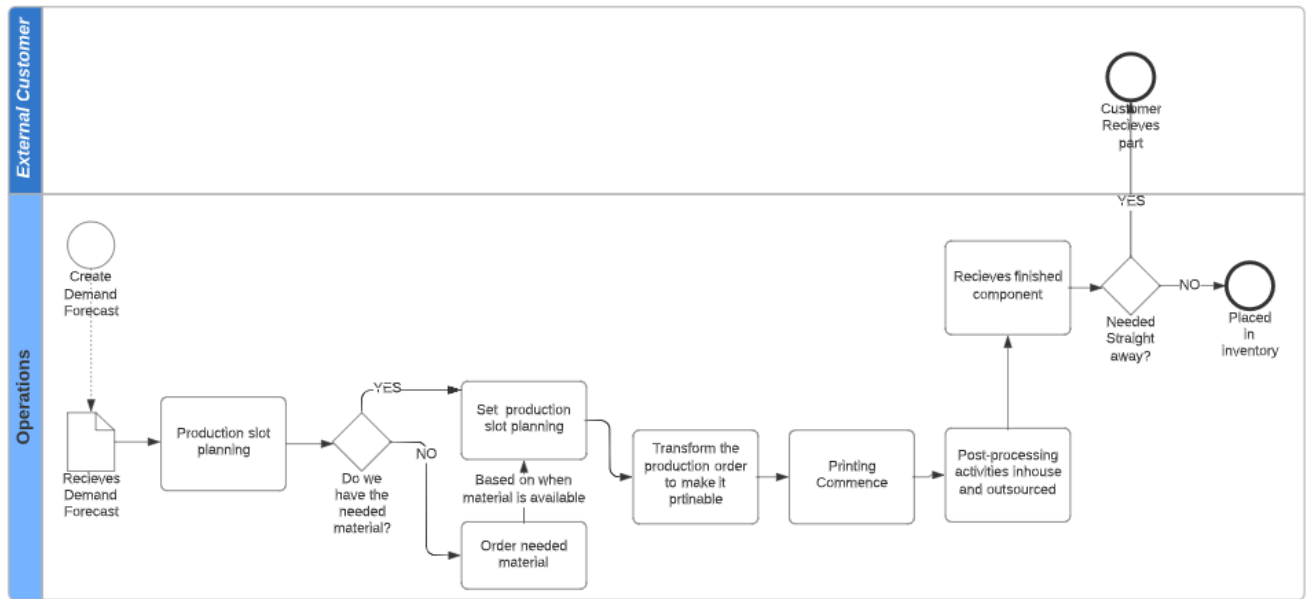


Figure 3. Simplified process map of SE's AM serial manufacturing (Our own illustration).

4.2 Findings SRQ

The following sub-headings are the themes identified through the inductive thematic analysis. Below each sub-heading, the additional sub-headings are the codes used connected to the theme. A visualization of the themes and connected codes is available in Table 7.

Table 7. Codes and Themes for SRQ

Codes	Themes
Production ready CAD files	Information Storage
Data quality assurance	
Enabling printing on-demand	One Stop Order Fulfilment
Order to fulfilment possibility	
Lead-time visibility	
Connection to production planning	
Information and communication platform	Simplified Information Sharing
User friendliness	
Control over information sharing	Information Protection
Information protection capability	

4.2.1 Information Storage

4.2.1.1 Production Ready CAD files

The desire for a DI to function as a form of information storage was evident in all interviews. In a DI CAD files need to be stored digitally and be completed in a way that allows the file to be used for production straight away when demanded. As Respondent E stated, *“From an internal perspective, it [a DI] would be to have the right and enough information stored in our systems to quickly be able to produce a component on-demand, instead of having to place it in a physical inventory.”* To further signify the importance Respondent F puts emphasis on production-ready CAD files as the CAD file truly reflects the output after the printing process. *“The [CAD] model is really the most important and controlling, it must be completely correct. We had CAD models on parts a while back as well, but then it was not as exact, the measurements were not always right.”*

4.2.1.2 Data Quality Assurance

The quality of the information stored that works as building blocks to realize a DI is important since this is considered an integral part of the success. Because as Respondent C said *“I am thinking specifically about the big monetary value with printing. But there is also a cost related to time. We are talking about millions of dollars and a lot of time and that is the risk you are taking if something does not come out correct. It is therefore particularly important to make sure that the information is correct to make the correct decisions in the printer.”* Respondent A further mentions that to ensure information quality the information that is stored within the DI should come from already established systems. *“If we were to have a DI it would have to gather master data which we already use. We cannot make up new numbers for articles for example. We need it to be tied to information that we already have.”*

4.2.2 One-Stop Order Fulfillment

4.2.2.1 Enabling Printing On-Demand

The functionality of a DI must enable printing on-demand and as Respondent G mentions, that on-demand production entails moving the customer order point to the end. *“I am thinking that DI is to print from order. Meaning you move the customer order point all the way to the end”.* Another important factor is that the DI and on-demand printing should function in a way in which physical inventory becomes unnecessary. *“For example, say we have a component in storage, and we can get it out of storage in 5 days. In this case, one could be fine with having*

it stored digitally instead and being able to both print it and deliver it within 10 days” (Respondent E).

4.2.2.2 Order to Fulfillment Possibility

Respondent B expressed that being able to place the orders on the platform was of importance. *“That I have a DI, a list of available parts, that I can click on and preview what I would order. That I could choose between a number of options and place the order on that platform so that I do not have to leave the platform and go to another site and sign in somewhere else. It should be a one-stop thing, and I also expect to be able to pay there.”* However, other functions regarding the financial flows were disagreed upon. *“In my world, I would define merely being able to place the order there as a DI, I am not sure if the payment service should be included”* (Respondent D). The possibility to place orders in the system was expressed by Respondent F as favorable as it would otherwise require unnecessary work. *“It is also important that the order happens in this system otherwise there would be extra work going into another system to place orders.”*

4.2.2.3 Lead Time Visibility

The necessity for lead time visibility in DI was evident. *“Lead time is a demand. we always need to know the lead time, given that I need to know if we need to secure the availability, then I need to know what time it takes”* (Respondent G). Expressed from another perspective Respondent F stated that *“There are two things that are important if we speak about customers. How much does it cost and when can I have it? It's those two. Therefore, I think that a DI would have to be able to handle that. Otherwise, I might as well call someone and ask about the component myself. If we are going to benefit from having things digitally, then these numbers must be visible there.”* Without lead time in the DI practitioners would still have to put effort into searching for the information. The inclusion of lead time visibility would eliminate otherwise unnecessary steps. *“Perhaps we do not need people sitting and telling us when we can have parts, perhaps the system can tell you when you can have your component, without anyone sitting back-office answering.”* (Respondent H).

4.2.2.4 Connection to Production Planning

DI would need to have a connection to production planning. *“It has to be connected to the manufacturing availability or scheduling...I think that the future production plans could be important for a DI”* (Respondent F). The need of having a connection to production planning directly affects lead time visibility. Lead time visibility would be what the users of a DI would

see, whereas the connection to production planning would be the function enabling lead time visibility.

4.2.3 Simplified Information Sharing

4.2.3.1 Information & Communication Platform

Being able to easily access and share information in a DI was considered important. As Respondent A expressed, *“Make the information that exists available and easily accessible for the people that need the information. In the end, we need a lot of physical components, but I feel like digitalization is making information accessible in a smarter way.”* Respondent D added that *“It is a collaboration platform.”* The collaboration by sharing of information between different departments was emphasized. *“The thing that is hard with keeping it digital is linked to the entire chain. You can't skip a step because then it won't work. If you can't see what the situation is in the workshop, or the lead time then the whole thing is going to crash. Because then you still must contact the planners and then it may take a week to get a set date for the manufacturing. Then you have to manually insert it into a system and then you have to account for human errors which may take additional time. We need to make the entire chain digital for it to work.”* (Respondent F).

4.2.3.2 User-Friendliness

“The problem today is that people cannot find the data” (Respondent C). Thus, another important feature of a DI is to consider is user-friendliness. *“I can see the times and costs in our ERP system. But my wish is for a DI to provide that same information but to do so in a user-friendly way.”* (Respondent A).

4.2.4 Information Protection

4.2.4.1 Control Over Information Sharing

The ability to have control over the flow of information in a DI is important. Respondent D mentions the ability to limit and extend the information that people will have access to. *“We can steer the information from existing systems what information and data we want to send to the DI platform. And in the platform, we can control e.g., the suppliers and what information they get access to. We may have 10 things available, but they only have access to see 1.”* Respondent B adds *“We can publish our information according to our rules just like we want it.”*

4.2.4.2 Information Protection Capability

The concern of protecting stored information in a DI was stressed by Respondent C, *“If you think of the cloud, you have to always assume that the other people are people you do not trust.”* Information protection is especially important considering sensitive information that should not be shared with whoever. *“We have intellectual properties that we cannot share with whomever internally and externally.”* (Respondent D).

4.3 Findings MRQ

In this section, the themes and codes following the inductive thematic analysis of the MRQ data will be presented. Benefits will be presented first and later, challenges

4.3.1 Benefits

This section will present findings related to the perceived benefits of DI. The sub-headings illustrate themes and additional sub-headings illustrate codes. A visualization of the codes and connected themes is available in Table 8.

Table 8. Codes and Themes for MRQ Benefits

Codes	Themes
Reduced holding cost of materials	Reduced Risk & Cost
Reduced physical inventory	
Moving the customer order point back	
Reduced manual steps	Process Optimization
Reduced risk of human error	
Centralized data	
Easier access to information	
Learning from gathered data	Further Development
Digitalization can inspire further digitalization	
Reduced lead-time	Increased Competitiveness
Increased flexibility	
Increased sustainability	

4.3.1.1 Reduced Risk & Cost

4.3.1.1.1 Reduced Holding Cost of Materials

Respondent 10 discussed the implications of a DI downstream and pre-production. *“If we have powder instead of holding materials in various diameters and sizes etc., then we’d diminish our raw material inventory substantially. It would also be fewer things and suppliers to keep track*

of.” Focusing on how the material needed for AM compared to CM could reduce the complexity and holding cost of the material inventory.

4.3.1.1.2 Reduced Physical Inventory

The possibility to reduce physical inventory upstream or post-production of parts was discussed as a benefit. Following the digitalization of parts, placing the DSPs in a DI could lead to the reduction of physical inventory. As Respondent 18 stated, *“We wouldn't have to buffer anything physically, so without tying up capital we could meet the customers' demand”*. Reducing physical inventory is linked with reducing tied-up capital and risk.

4.3.1.1.3 Moving the Customer Order Point Back

Respondents 9 indicated that the possibility to adopt a make-to-order approach with the aid of DI was a benefit that would reduce risk. *“With this, we could wait longer with ordering and producing things, and to produce we would only need to have powder on our shelves, that can be used for any part really.”* The risk would be diminished since it requires less speculation.

4.3.1.2 Process Optimization

4.3.1.2.1 Reduced Manual Steps

A benefit of DI is the possibility to reduce manual steps. The reduction of manual steps was discussed in general but mainly highlighted in the order management process *“The time it takes to place orders, the time you spend waiting for replies. If you can do something straight away instead, by reducing steps, things we do today that we wouldn't even have to do if we had a DI, then it's really adding value.”* (Respondent 5). Similarly, Respondent 3 expressed that reduced manual steps would simplify the order process, *“To be able to place orders in a system, get an approximate lead time, and not having to involve a lot of disciplines or people to get the order to go through to production would simplify things.”*

4.3.1.2.2 Reduced Risk of Human Error

According to the respondents the reduction of manual steps, naturally leads to a reduced risk of human error. *“If we reduce the number of steps needed then we're also reducing the risk of handling errors”* (Respondent 5). The reduction of manual steps may also reduce the number of people involved. As expressed by Respondent 6 *“If fewer people are involved, then the risk of errors in handling is reduced.”* Lastly, a reduction in human errors following a decrease in people involved could also improve the quality of the information flow *“Heightening the information quality to really make it easier to make the right choice.”* (Respondent 17).

4.3.1.2.3 Centralized Data

By centralizing data in a DI, more structure could be achieved. *“Structure and structuring things are good, and that’s what this [a DI] would do. It would have to be the right CAD model, etc.”* (Respondent 19). An increased structure might be particularly important for new segments such as AM. *“Considering that the AM organization is quite new there is a lack of standardization in our processes. I believe DI could be one way of solving this.”* (Respondent 4).

4.3.1.2.4 Easier Access to Information

Following the data centralization improved accessibility of information through digitization and placement in a DI was perceived to be obtained. *“By digitalizing it would be easier for us to keep track of and find the information, as it would be in a system.”* (Respondent 4). To easier access information could be beneficial in different ways. Respondent 15 expressed the value towards customers *“the value of a DI could be that it enables easier sharing of information with customers”*. While Respondent 2 expressed the internal value *“If our service organization needs a certain component for a machine, it is an ordeal to find the information about the lead time and even when they have that information there is an 80% chance that it is incorrect, so they still need to double-check it.”*

4.3.1.3 Further Development

4.3.1.3.1 Learning from Gathered Data

A perceived value can be seen in collecting data from DI for analysis *“I can see the finesse with having a lot of data available to analyze”* (Respondent 12). Respondents saw the possibility of learning from the data to improve. *“Perhaps a lot of value would lie in gaining more knowledge about what’s really going on. Finding those things and understanding them. Gathering data in and from the DI to learn things, things we maybe didn’t even know we didn’t know.”* (Respondent 15).

4.3.1.3.2 Digitalization Can Inspire Further Digitalization

Apart from learning from gathered data, respondents were also under the impression that the introduction of a DI would inspire further digitalization within the organization. *“I think that there are plenty of possible positive spin-offs on this. So, I think we should go ahead and try. It doesn’t feel like there is that high risk involved in trying.”* (Respondent 20).

4.3.1.4 Increased Competitiveness

4.3.1.4.1 Reduced Lead Times

Respondents stated that according to their experience, producing components through AM is faster than CM. *“The fact is that on a material level it is faster to print than to cast.”* (Respondent 17). Thus, lead time s in production can be reduced through AM. Combining AM with a DI that reduces manual steps and the information flow can thus yield reductions in the overall lead times. *“Lead times are considered a risk, if we can shorten the lead time, we reduce risk and that is an advantage. If we can produce, make to order with short enough lead time we won’t have any risk.”* (Respondent 18). From a service-oriented perspective, reduced lead time can increase competitiveness.

4.3.1.4.2 Increased Flexibility

Through AM organizations can obtain increased flexibility, *“You don’t need tools in the same way with AM, well you need some tools of course but it feels more flexible. You don’t have to worry about obtaining a special tool from a supplier or anything, which usually takes a lot of time.”* (Respondent 19). Respondents also stated that lead time reductions following the DI implementation can lead to increased flexibility. *“With shorter lead times we can be more flexible.”* (Respondent 17).

4.3.1.4.3 Increased Sustainability

According to the respondents’ experience AM offer sustainability benefits. Both in terms of resource efficiency and reduced emissions. As Respondent 20 put it *“In conventional manufacturing, much of the material falls into the waste box next to the machine. With AM you have a better material utilization degree.”* While Respondent 14 emphasized the decreased emissions obtained through AM *“You can increase the performance and reduce emissions, and I believe that’s what customers want to purchase.”*

4.3.2 Challenges

This section will contain challenges related to DI. The sub-headings illustrate themes and additional sub-headings illustrate codes. A visualization of the codes and connected themes is available in Table 9.

Table 9. Codes and Themes for MRQ Challenges

Codes	Themes
Export laws compliance	Rules & Regulation
Forced reliability on organizational rules	
Post-processing necessity	Post-processing
Post-processing lead-time degrades the value of a DI	
Outsourced post-processing causes lack of control	
Risk of human errors	Operation issues
AM too slow for a DI	
Reliability of the AM process	
Organizational resistance to change	Change Management
Individual resistance to change	
How to include conventional in DI mindset	
DI owner issues	Strategy
Knowing what DSP to include in a DI	
Calculate lead-time to remove inventory	
Capacity calculation to maintain a DI	
Over-capacity cost	Profitability
Over-capacity cost vs. Inventory cost	
AM is costly	
Batch production necessity	
Keeping DI updated	System issues
Synchronized updates	
Information protection issues with DI	

4.3.2.1 Rules & Regulations

4.3.2.1.1 Export Laws Compliance

One challenge is export controls. The current laws and regulations regarding transactions and trade between different countries that organizations must abide by. *‘The thing that I would like to highlight here is export control. Export control on its own is a major problem area. “Who's allowed to order and from where? In the realm of Siemens Energy, it is very important to understand the nationality of the person placing the order.”* (Respondent 11). Organizations are thus not allowed to sell certain types of products to anyone, anywhere. Certain information regarding the operations of the case organization is considered sensitive. Respondent 4 mentions export laws relating to information sharing between different global actors. *“The sharing of information, how to access the information from different systems, and how to communicate. We have laws about export control. This means that not everyone is allowed to work or see with certain things.”* It is important to control the information to ensure that no information is made available to the wrong person.

4.3.2.1.2 Forced Reliability on Organizational Rules

Organizations must often abide by the decisions made on a global level. *“Had we been an organization limited to Finspång it would be easier to implement a digital inventory. We are however constrained by the decisions made on a higher global level. The global decisions kind of hamper our attempts at decision-making. I believe it would be easier if we were a smaller organization or did not have to follow along with the global decision making”* (Respondent 11). Any new system implemented must accommodate the current enterprise resource planning system. As said by Respondent 8 *“The thing is, SAP is considered the backbone of our operations and that hinders us a little bit. We can't make our own solutions because in the end it must be connected to SAP.”* Thus, challenging the implementation of a DI.

4.3.2.2 Post-Processing

4.3.2.2.1 Post-Processing Necessity

Reliance on post-processing to produce components with AM is seen as a challenge. As Respondent 17 said, *“The lack of few simple components that don't need post-processing is a challenge and the big variety in existing components with low volumes.”* Post-processing adds lead time and complexity and is therefore perceived as a challenge in the realization of a DI.

4.3.2.2.2 Post-Processing Lead Time Degrades the Value of a DI

Post-processing can be regarded as a challenge since it is believed to hamper some of the value with a DI. *“The lead time is quite long. The printing is fast compared to conventional methods but the post-processing is rather lengthy so we already have a lot of development to do for it to be as fast as we would like it. We need to reduce the lead time to be faster”* (Respondent 8). If the post-processing activities are outsourced the lead time could be lengthened, thus further decreasing the value of a DI. *“Take our serial production as an example, the chain of steps to have a finished component is enormous, both inhouse and externally to Italy and Germany for example. In that sense, it is very unfavorable. If we could do all steps in Finspång it would be a lot better”* (Respondent 11). Additionally, conventional methods in post-processing are considered ill-fitting in the inclusion of a DI. *“Automation would give us better conditions for a DI and when you lose the digital part you lose some of the benefits with it and it is basically back to normal.”* (Respondent 12).

4.3.2.2.3 Outsourced Post-Processing Causes Lack of Control

Outsourced post-production activities can be linked to increased risk and cost. According to Respondent 7, it can be regarded as a challenge in the realization of a DI *“I think the customer*

wants us to take responsibility for the entire chain but that's not the case. We've seen in our analysis that each time the production is transferred outside of our gates it is coupled with risk and cost, both when it goes out and comes back. We have the same concern internally as well, that it is related to cost and risk.” If the manufacturing organization does not own the post-processing steps the control over the lead time is reduced. As Respondent 10 stated “one should be prepared for that if we do not own the post-processing steps necessary to produce the things we have in a digital inventory, we might have to look around for someone who can do the post-processing within the given time frame. So, we need to have everything within our walls to get some sort of speed.”

4.3.2.3 Operations Issues

4.3.2.3.1 Risk of Human Errors

The first challenge concerning operations is the risk of human errors. “To make it [a DI] work everyone must follow along. If you do something in production without the notice of the system people who check the systems will believe in truths that are false and that may cause errors. Everyone must follow the new way of working religiously.” (Respondent 15). Thus, the challenge is to detect human errors and have a standardized way of working.

4.3.2.3.2 AM too Slow for a DI

AM process can be considered quite slow in the context of on-demand production, and the actual production process will not be shortened by the inclusion of a DI. “The thing is, with a DI we are still delivering physical components and there is still a long physical process to get a component even if we say we can provide it through a DI. The time aspect is still there since we are providing a physical product.” (Respondent 16).

4.3.2.3.3 Reliability of the AM process

The reliability of the AM process is challenging for manufacturers. “Something that I see as a challenge for DI is when we update the software in the printing machines. If it is something we print frequently we can see if it affects the printability of the component. But if it is something more complex that we print less of then it is not as easy. If we then get an order on that component with expected delivery in 4 weeks. It would be hard” (Respondent 13). The reliability is affected by the sensitivity and lack of knowledge about the AM process, affecting the output product, which may influence the functionality of a DI. Respondent 4 also points out uncertainty in printed components as a challenge. “Our biggest obstacle from my perspective is the quality of our components. We are not in full control of our printed components just yet. It

may differ between different printers in the spread of the powder. This aspect makes me especially nervous when printing new components.” Overall, DI relies on a developing production method, making it difficult to predict outcomes. Poor outcomes can hamper the on-demand promise.

4.3.2.4 Change Management

4.3.2.4.1 Organizational Resistance to Change

When things are already perceived as “good,” the desire for development may become lost in organizations. *“There is a risk when things are already "good" that you don't realize the upsides with development. Therefore, I believe it is important for us to research external trends and surrounding to understand the pace we need to be at. I believe in constant change and development.”* (Respondent 12). Without development, there is a risk to stagnate and lose competitiveness.

4.3.2.4.2 Individual Resistance to Change

Getting individuals onboard the change of a new system was perceived as challenging. As Respondent 15 stated, *“To get people to join in, scale it up and get people convinced”*. The increased information sharing following a DI could also increase resistance. *“There is also a fear internally between different departments with sharing data. People are used to it being their responsibility and you may see it but then you have to ask for it. To suddenly have it all visible in a system for anyone to see may be challenging. You should not underestimate that feeling.”* (Respondent 1). Failure to successfully convey the benefits of a DI could lead to users' resistance.

4.3.2.4.3 How to include Conventional in DI mindset

There is a perceived challenge in merging two workshops into one philosophy. As Respondent 13 expressed: *“With some of our components, half is made in AM and the other half in conventional.”* Manufacturing organizations often have a make-to-stock strategy while AM in a DI focuses on a make-to-order strategy. Thus, merging philosophies could be a challenge in the implementation of a DI. *“Today there is a divide between the AM and conventional workshops, they have different mindsets and paces for their production. It will not work if it stays the same as now where every product is placed last in the queue this needs to be streamlined to work with the addition of overcapacity. We have had a challenging time implementing two manufacturing philosophies in the same workshop.”* (Respondent 20). DI requires collaboration between CM and AM considering post-processing activities.

4.3.2.5 Strategy

4.3.2.5.1 DI Owner Issues

The decision in project ownership and decision-making authority is a challenge related to DI. *“This is not specific for DI but for all project management you need to have stakeholders and a project owner. Who's got the right to make decisions? This has got to be defined beforehand and there can only be one owner. The owner is the person who decides what decisions to make and when we are pleased with the result.”* (Respondent 11). As DI is a new concept it is difficult to determine the most suitable function for project ownership.

4.3.2.5.2 Knowing What DSP to Include in a DI

Deciding what components to include in the DI is difficult, as expressed by Respondent 2, *“What kind of components would be most useful in a DI? I think we need to focus on that because it will cost a lot to maintain and keep rolling so we need to think about where and with what components we see the largest gain.”* Connecting the gain to cost is a potential way of choosing components to include. Another way to choose components to include is in relation to volume *“The challenge lies in finding the volume in the component we want to include in DI, seeing as we don't produce large volumes”* (Respondent 17). The difference in responses is an indication that the objective for component inclusion needs to be established.

4.3.2.5.3 Calculate Lead Time to Remove Inventory

A perceived challenge is the concern of matching on-demand production with the market demand and expected delivery time. As Respondent 20 expressed, *“For on-demand DI to be an alternative you need to have a delivery time that matches the demands in the market and is short enough to ensure that you won't have to keep physical inventory.”* The objective with DI is to remove physical inventory. To achieve this organizations must establish a lead time threshold acceptable to remove inventory while also upholding market standards.

4.3.2.5.4 Capacity Calculation to Maintain a DI

Maintaining and calculating capacity to ensure on-demand production in a DI is necessary. *“On-demand can be ruined completely if the activity in the workshop increases. Suddenly, we have new delivery times which are not interesting to the customer anymore and then we end up with an inventory after all. I believe it is important to calculate the margin of capacity that we must keep to maintain our level of service.”* (Respondent 19). The calculation is necessary to ensure sufficient capacity, no physical inventory, and uphold promises made to customers.

4.3.2.6 Profitability

4.3.2.6.1 Over-Capacity Cost

In an on-demand scenario such as in the case of DI, organizations would have to have over-capacity to be able to produce once orders are placed while also meeting some sort of acceptable lead time. *“If we are to do this on a make-to-order basis, then the demand can occur suddenly, since it’s not planned, we need to make sure that we have the capacity for the orders placed. And that’s a cost we need to consider.”* (Respondent 8). The challenge lies in determining how much over-capacity would be needed to operate the DI and determining the cost of having over-capacity.

4.3.2.6.2 Over-Capacity Cost vs. Inventory Cost

Following the reasoning of having over-capacity and the cost of over-capacity, questions were raised regarding if the reduced inventory cost was enough to pay for the over-capacity needed in a DI. *“We could challenge this thought of over-capacity being expensive. Building physical inventory and producing to optimize the machines and production capacity is more traditional. But it is interesting to challenge this perception – is it better to have free capacity instead of inventory?”* (Respondent 18). To find profitability in a DI, the cost of holding inventory needs exceeds that of having over-capacity.

4.3.2.6.3 AM is Costly

Respondent 16 stated that AM is a costly production method, *“Right now, AM is too expensive.”* Compared to CM AM is considered costly. *“We need to be prepared to have high costs on components in a DI. Because it is difficult to match AM with CM in terms of price”* (Respondent 14). Matching the market price of components is difficult with AM *“With our easier components that may only require 1-2 post-processing steps we would be able to send them within 3-4 days. However, the dilemma here is that then we are about 2-3 times more expensive compared to the market price because AM is a very costly production method.”* (Respondent 7) Thus, finding the profitability in a DI might prove difficult.

4.3.2.6.4 Batch Production Necessity

In the context of a DI and the on-demand principle, the need for batch production due to AM being costly may pose a challenge. As respondent 14 said *“One-piece production is expensive, so since we want to have it digitally, we can’t print batches. If we do and you only need two parts, well then, you’d have to place the other eight in physical inventory, and then we don’t have the make-to-order principle. So, we need to find the right level of everything.”* Finding

profitability in printing single components instead of batches is challenging but necessary to not build physical inventory and produce on-demand.

4.3.2.7 System Issues

4.3.2.7.1 Keeping the DI updated

One challenge in the functionality of a DI is to ensure that the stored information is updated. *“I think one challenge will be to keep the system alive, we need to use it and keep it updated.”* (Respondent 2). To maintain the system and data, *“Everyone must understand why and how to work with it to make it a success. I believe it to be a challenge to not get lost in this process.”* (Respondent 19). To ensure information quality everyone must know how to work with a DI.

4.3.2.7.2 Synchronized Updates

Updates on the components or printers must be synchronized to ensure the functionality of a DI. *“There are some rules that state that if you make substantial changes, you must change the drawing number and that will increase the cost. If you keep things in a DI, the components must be regarded as going all the way. If you make changes, you must control the whole way to make sure that it does not change anything.”* (Respondent 1). Otherwise, it could affect the printability or quality of the components, largely due to the sensitivity of the AM process.

4.3.2.7.3 Information Protection Issues with DI

Lastly, protecting sensitive information is also seen as a challenge. *“If the entire recipe is revealed, anyone could just get a similar printing machine and copy it. We have always been scared for the recipe to be revealed because there you will get all the information on how to prepare the components and post-process.”* (Respondent 1). Information protection is often a challenge when dealing with digitalization and digitized products, especially when handling sensitive information.

5. Analysis

In this section, the findings presented in Chapter 4 will be analyzed and contrasted to the previous theoretical knowledge presented in Chapter 2.

5.1 Analysis for SRQ

5.1.1 Information Storage

According to our findings, a DI needs to work as a system to store information. This might be the most straightforward understanding there is of a DI. Similarly, Ballardini et al. (2018) referred to this as a virtual library. Although Ballardini et al. (2018), presumed that the virtual library was to be publicly available, which is opposite to our non-public context. Moreover, our findings placed great emphasis on the need for CAD files placed in the DI i.e., the DSP, to be production ready. Araújo et al. (2021) explained that a DI would work as a storage space for digital files, to enable on-demand production. Our findings extend this understanding. As emphasized in our findings – for CAD files to enable on-demand production they need to be ready for production. Moreover, the need for production-ready CAD files implies that a DI is not suitable for prototypes. As prototypes are not considered ready for production.

5.1.2 One-Stop Order Fulfillment

From our findings, we were able to identify that the DI should include functions that enable order processing and placement within the system. This finding can be related to Wang et al. (2019b) definition of cloud-based AM where the customers can place orders by uploading a model in the system and expect delivery of a component. In our case, the production-ready CAD file should already exist in the DI for internal purpose use and order placement. Our findings of the necessity to be able to process and place orders via DI is also necessary to enable an on-demand production. This is since the customer order point is the starting point of the production process. Moreover, another function that should be implemented to ensure one-stop order fulfillment is the ability to see the lead time in connection to the ordering process. In the Wang et al. (2019b) definition of cloud-based AM, they mention the fact that the cloud AM system should work to make the scheduling of production easier. Despite not explicitly stating a direct connection to lead time, Wang et al. (2019b) are alluding that there is some connection to production planning by emphasizing the scheduling capabilities of cloud-based AM.

5.1.3 Simplified Information Sharing

The idea that DI should be a platform for information sharing as found through our interviews has not been stated explicitly in previous research. However, it has been indicated that it is

fundamentally what occurs in cloud-based AM, publicly available virtual libraries, and digital inventories. As cloud-based AM functions as a platform to upload data (Wang et al., 2019b). While virtual libraries contain publicly available data (Ballardini et al., 2018), and DIs are said to contain product information (Araújo et al., 2021). I.e., in all cases sharing or enabling the sharing of information. However, we have added the perspective of information sharing as a function necessary in the DI concept, rather than information sharing just being a consequence. Another aspect of information sharing which could be drawn from the sets of data is the connection to user-friendliness. Necessary to ensure that the stored and shared information is easy for the user to obtain and interpret. User-friendliness is not mentioned explicitly in previous literature. Although, both cloud-based AM and Virtual libraries have a service-orientation focus (Baumann & Roller, 2017; Ballardini et al., 2018), one could therefore assume that user-friendliness is an important consideration.

5.1.4 Information Protection

Previous research has focused on questions regarding sharing information with external customers. Ballardini et al. (2018) discussed the necessity to be able to protect IP in the form of CAD files when sharing data in publicly available virtual libraries. Similarly, Baumann & Roller (2017) speaks of the importance of IP rights and information in cloud-based AM. Thus, previous research strengthens our findings regarding the importance of information protection capabilities in a DI. Although, our findings concern a non-publicly used DI information protection possibilities are necessary despite not sharing information outside of the company. Information protection should therefore be included in the realization of a DI.

5.1.5 Summarizing the Analysis for SRQ

From our analysis, we found that practitioners perceive that a DI needs to consist of: information storage, one-stop order fulfillment, information sharing, and information protection possibilities. From the findings, it can be understood that the DI is a system and not just a shift in the conventional make-to-stock strategy of manufacturing organizations. Nevertheless, the DI facilitates a strategic shift to an on-demand way of working.

To ease the readers' understanding of the process flow in a DI, a simplified visualization is provided in Figure 4 below. Compared to the simplified process flow of SE's current operation visible in Figure 3, a clear increase in instantaneous information sharing is visible. Resulting in a reduced necessity for manual process steps.

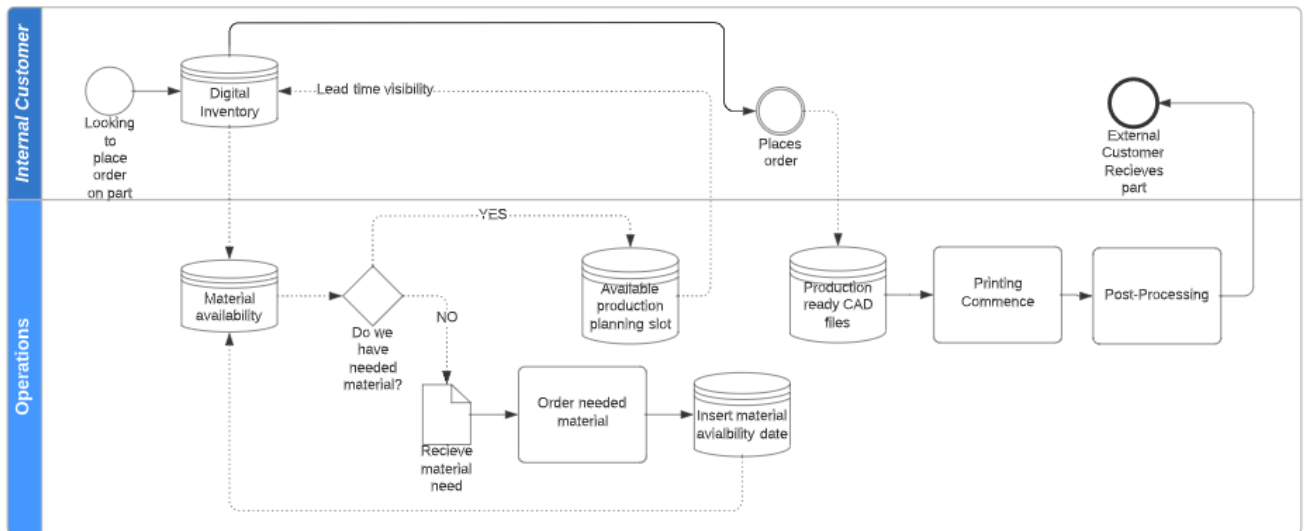


Figure 4. Simplified process flow of a DI (Our own illustration).

5.2 Analysis for MRQ

5.2.1 Analysis for MRQ Benefits

Through our interviews and thematic analysis, we found 4 themes of benefits of adopting a DI. Below we will discuss each of the themes and contrast it with previous theoretical knowledge.

5.2.1.1 Reduced Risk & Cost

We identified the possibility to reduce risks and costs by introducing a DI as a perceived benefit. The possibility to reduce holding costs of materials, reduce physical inventory, and move the customer order point could reduce the risks and costs involved in speculating demand.

Since only one material is needed to print, and the form of the input material for AM is less bulky than materials for CM, it was perceived as a benefit for the pre-production inventories. Reduced risks would be obtained through the stocking of fewer materials. Fewer materials needed for production combined with lesser space required for stocking the AM input materials were said to possibly reduce material holding costs. The input material space has also been discussed by Peng et al. (2018), who spoke about it in terms of reduced costs of transportation due to less required space. Similarly, to us, Gupta et al. (2020) and Oettmeier and Hofmann (2016) also found benefits pre-production. They stated that due to the reduced need for different input materials, AM requires fewer suppliers, and thus has the possibility of reducing supply chain complexity.

Similar to our findings, most previous research has identified the possibility of reducing physical inventory post-production as a benefit connected to AM and AM-enabled systems (Araújo et al., 2021; Javaid et al., 2021; Togwe et al., 2019; Chekurov et al., 2018; Kretzschmar et al., 2018a; Holmström & Gutowski, 2017; Thompson et al., 2016; Holmström et al., 2010).

Previous research has found the possibility of producing on-demand a benefit of adopting AM (Kretzschmar et al., 2018a; Peng et al., 2018; Holmström & Gutowski, 2017; Holmström et al., 2010). Or as Ballardini et al. (2018) referred to it, adopting a just-in-time manufacturing strategy. Indeed, AM holds promising potential for increasing the speed of production compared to CM. Enabling on-demand production. We would argue that AM alone cannot establish an on-demand production. For the customer order point to actually be moved back, information flows would have to be altered. This could be obtained through the introduction of a DI.

5.2.1.2 Process Optimization

Our findings state that there is a possibility to optimize processes through the introduction of a DI. Respondents perceived that the introduction of a DI would reduce manual steps needed in various activities, thus also reducing the risk of human error. The removal of physical steps can contribute to an easier order process. The introduction of DI could also enable data centralization. All of which can be perceived as benefits. Ballardini et al. (2018), essentially found the same benefits when researching publicly available virtual libraries. The order placement process in our case is internal which could reduce the need for e.g., emails. However, we can see the similarities with Ballardini et al. (2018) identified benefits of facilitating the purchasing process, which concerns external actors and monetary transfers. Additionally, Ballardini et al. (2018) found that publicly virtual libraries could aid in centralizing product data, by providing a library of parts. Although the DI in this research is not publicly available, the function of centralizing product data is the same. This has been identified as a way for practitioners to easier find information without having to contact others. Thus, shortening the information flow.

5.2.1.3 Further Development

Much potential can be seen in the possibility of learning from data gathered in the DI. Through this, practitioners expect to learn more about current issues with AM, potential issues that may arise with a DI, and gain insights on matters of a surprising but valuable nature. Although previous literature has not identified further development as a benefit of AM-enabled systems learning from gathered data to counteract challenges identified. Namely, the challenge concerning the reliability of the AM process. Causing variability in product output (Ford & Despeissie, 2016; Thompson et al., 2016), due to not knowing the process well enough (Chekurov et al., 2018). With more knowledge about the processes, practitioners expect further developments to be made. Moreover, our findings indicate that the practitioners perceive the adoption of DI as a catalyst for more digitalization. Perceived as beneficial for the organization. This reasoning has not been articulated in previous research.

5.2.1.4 Increased Competitiveness

DI can be perceived as a source of increased competitiveness. With the shortened information flow and reduced manual steps achieved through DI, lead time reductions are probable. Increasing the competitiveness of organizations. This benefit of AM-enabled systems has not been addressed in previous literature. However, practitioners stated that lead time reductions are made possible through AM, as it is said to be faster than CM. This finding can be corroborated by benefits identified by Gupta et al. (2020) and Kretzschmar et al. (2018b). Previous literature is however slightly contradictory with regards to AM being a fast production method. In the research of Chekurov et al. (2021) and Ford and Despeissie (2016), the AM process was said to be slow.

Another source of increased competitiveness obtained through DI is the increased flexibility. Resulting from the reduced lead times and the AM machine. The flexibility of the AM machine is perceived as beneficial. Similarly, Araújo et al. (2021), Togwe et al. (2019), and Kretzschmar et al. (2018a) found the flexibility of AM beneficial. Oettmeier and Hofmann (2016) referred to this as the versatility of the machine. While Holmström et al. (2010), focused on the reduced need for tooling due to the flexibility of the machine.

Lastly, a perceived source of competitiveness is the decreased environmental impact of AM. By using the AM technology in production instead of purely CM, waste reductions can be achieved. This is due to the additive layer-by-layer build, rather than the subtractive process of

CM. There seems to be a consensus about this benefit in previous literature (see. Arjaúro et al., 2021; Javaid et al., 2021; Gupta et al., 2020; Wang et al., 2019a; Holmström & Gutowski, 2017; Ford & Despeisse, 2016; Gebler et al., 2014; Holmström et al., 2010). Thus, we would argue that the resource efficiency of AM is a well-established benefit. Moreover, practitioners' experience is that AM produces fewer emissions than CM. Gebler et al. (2014) also said that reduced emissions were a benefit obtained through AM. There are, however, contradictory opinions regarding AM's sustainability impact in previous literature. Specifically, Peng et al. (2018) question AM's environmental impact from a lifecycle assessment point of view. Regardless, this research has found that increased sustainability is a perceived benefit of DI.

5.2.2 Analysis for MRQ Challenges

Under this heading, the findings from the thematic analysis will be presented. Through our analysis process, we were able to identify 7 themes of challenges with implementing and realizing a DI.

5.2.2.1 Rules & Regulations

One perceived challenge of DI is already instated rules and regulations. More specifically export rules and laws regarding allowed trade and transactions between different countries. Like many others, the organization is restricted by these rules. Previous literature has not mentioned export laws as a challenge; however, other rules and regulations have been identified as a challenge. Namely IP rights (Ballardini et al., 2018). Thus, we can see that various rules and regulations are challenges for AM-enabled systems. Organizational rules are also a challenge in DI. More specifically the forced reliability on decisions made on a global level means that it may be hard to enforce change in one branch without approval on a higher level. The organization must conform to already established systems and must make sure that any inclusion in development is accommodating to their ERP systems. Despite the lack of previous mentions of challenges related to internal structures and systems, we would argue that this is a challenge when trying to enforce change and implement a new system.

5.2.2.2 Post-Processing

Post-processing is a challenge that needs to be addressed in the realization of a DI. Post-processing is a necessity in the production of most of the organizations' components. Despite not specifically mentioning lead time nor speaking in terms of a DI, Chekurov et al. (2018), Kretschmar et al. (2018a), Tofail et al. (2018) and Thompson et al. (2016) agree with the claims that the necessity of post-processing is a challenge. Considering that it is viewed as a challenge

for AM production, their claims should also be viewed as a challenge for DI. No previous literature addresses the added lead times effect on DI value. Moreover, Post-processing activities are currently performed using CM methods and sometimes require outsourced activities, thus negatively affecting the lead time. Long lead times degrade the value of a DI. Chekurov et al. (2021) and Ford and Despeissie (2016) mention the slow production process of AM as a challenge without specifying the exact activity one is referring to. Hence, one could suggest that they agree with the claims from our findings that post-processing activities add lead time. The added lead time following post-processing activities degrades the value of a DI, as the DI is meant to function on-demand. Additionally, outsourced post-processing is also perceived as a challenge since it may cause a lack of control in the processes. Ballardini et al. (2018) agree with the claims that outsourced activities cause a lack of control and increase uncertainty in the supply chain. In a DI the uncertainty and loss of control could be regarded as challenges in performing on-demand production.

5.2.2.3 Operations Issues

Human error is another challenge related to the realization of a DI. The idea is that a DI would remove manual steps and tie data together for increased availability. However, if incorrect information is inserted or the DI is used incorrectly, it will result in misleading information. Eventually resulting in declined functionality. The prospect of human error and the challenges it may pose to a DI is not considered in previous literature. The second challenge concerning operations is the fact that DI is reliant on the AM process, a process that is too slow to maintain an on-demand DI. This is since the aim of a DI is to provide physical components, but DI adoption will not remove steps in the actual manufacturing process. Previous literature shows contradictions in the perceived speed of AM. Gupta et al. (2020) state that AM is faster than CM, while Chekurov et al. (2021) and Ford and Despeissie (2016) state that AM is a rather slow process. Practitioners consider AM to be faster than CM, however, AM and following post-processing steps are considered too slow to sufficiently maintain an on-demand DI. The functionality of a DI is reliant on the performance of the AM process. This can be challenging for two reasons. Firstly, the process is sensitive. Upgrades in software may influence the output components. Corroborated by previous literature that states that variability in the component quality may be caused by a sensitive process (Thompson et al., 2016; Ford & Despeissie, 2016). Secondly, The AM process is still immature. Thus, producing components with sufficient quality is a challenge. Chekurov et al. (2021) agree that AM is still immature and thus not reliable. Kretschmar et al. (2018a) mention the uncertainty in the printing machines and how

it may cause inaccurate tolerances and levels, thus affecting the outcome of the components. One could therefore conclude that the reliability of AM process can be regarded as an operational issue in the realization and performance of a DI.

5.2.2.4 Change Management

The flow of information following DI adoption may induce individual resistance to change. Caused by a reluctance to share information openly between departments. Previous research agrees that resistance to change is a challenge in the realization of AM-enabled systems (Chekurov et al., 2021; Ballardini et al., 2018). More specifically, conservative ideas have been identified as a force of resistance. Organizational resistance to change may also be observed as one challenge lies in enforcing change when things are already perceived as good. Chekurov et al. (2021) also identified organizational resistance to change as a challenge. Differing from our findings, Chekurov et al. (2021) found that it stemmed from a reluctance to take on the magnitude of the change.

The organization uses both CM and AM in its AM production. Meaning that producing AM components entails work in two different workshops with two different philosophies. Merging these philosophies in the realization of a well-functioning DI is a perceived challenge. Merging of philosophies in traditional and AM manufacturing is not brought up by previous literature. However, as mentioned by Ballardini et al. (2018) CM organizations tend to be more conservative. Thus, despite no mention of the merging of the two-production methods one could assume the inclusion of the DI mindset in CM organization may prove difficult.

5.2.2.5 Strategy

With DI there are several strategic challenges to consider. Deciding on the project owner, who should have the last say in the decision making is a perceived challenge. Considering the lack of previous literature describing DI and its implementation, this specific topic has not been previously discussed. The decision regarding what DSPs should be included in a DI was found to be challenging. Practitioners offered different responses indicating the need to establish objectives for component inclusion. The uncertainty regarding choosing components suitable to include is according to Frandsen et al. (2020) true for the AM productions. Currently, there is a lack of information regarding the characteristics of components most suitable for AM production. This may be due to a lack of available product data (Knofius et al., 2016). The limited information on components could hamper AM production as well as the realization of

a DI. For DI inclusion additional characteristics might be necessary to consider. Moreover, calculating a lead time threshold acceptable to remove physical inventory and uphold market expectations is a challenge. Chekurov et al. (2021) and Ford and Despesse (2016) also argue that one of the challenges with maintaining AM is linked to the long production period, thus affecting the lead time. Despite it not being clear if it is the post-processing or printing that is time-consuming one can establish that estimating and maintaining a short lead time is a challenge in AM productions. Thus, a challenge in the realization of a DI. Lastly, the prospect of calculating and maintaining production capacity to ensure on-demand production was also deemed as a challenge in terms of strategy to ensure the functionality of a DI. Holmström et al. (2010), mentioned the need to consider capacity in their conceptual study on suitable supply chain approaches for AM. However, no previous AM literature has suggested capacity calculation models or the like.

5.2.2.6 Profitability

Finding the profitability in a DI may prove difficult. According to our findings, AM is currently a rather costly production method. Similarly, Chekurov et al. (2021), Ballardini et al. (2018), and Li et al. (2017) agreed that AM is costly overall. This can be explained by the high cost of raw materials (Ballardini et al., 2018; Thompson et al., 2016), and the high cost of the machinery (Li et al., 2017; Thompson et al., 2016). Although previous research has seen customization possibilities as a benefit with AM (Thompson et al. 2016), and that AM can make small batches economical (Oettmeier & Hofmann, 2016; Holmström et al., 2010), our findings indicate that batch production is a necessity to be profitable. The batch production necessity can be a challenge when implementing on-demand DI as it could reduce the effects of the physical inventory reductions. Furthermore, when producing on-demand, production processes must be set up to allow the manufacturer to have enough capacity to be able to deliver within a reasonable time. I.e., Over-capacity is needed. Knowing how much capacity is needed in the DI and the cost of that over-capacity needs to be understood before implementation. Holmström et al. (2010) conceptually talked about different scenarios' effects on capacity. However, their focus was not on determining the capacity needed. Rather Holmström et al. (2010) saw that there conceptually was a need to maintain a high utilization rate of capacity while reducing inventory to remain profitable. Our findings similarly indicate that there is a trade-off between the cost of having over-capacity and the cost savings obtained from a reduced physical inventory. This could be seen as a determining factor for the implementation of a DI. If the cost

of over-capacity exceeds that of holding physical inventory, manufacturers may not wish to implement a DI. Similarly, a risk calculation of both approaches would have to be considered.

5.2.2.7 System Issues

Keeping the DI updated and building a consensus on how one should operate within the system is a perceived challenge. Previous research has not specifically addressed this challenge in terms of AM-enabled systems. However, an explanation for this could be the potential resistance to change. Which has been identified as a challenge in this research as well as by Chekurov et al. (2021) and by Ballardini et al. (2018) regarding the implementation of other AM-enabled systems. A challenge identified is that updates in the system would have to be synchronized to not affect the final product. The necessity of synchronized updates has not been addressed in previous literature, however, Kretzschmar et al. (2018a) have identified the sensitivity of the AM process as a challenge. The need for synchronized updates is a result of the sensitivity and remains challenging due to the uncertain performance of the AM process (Ford & Despesse, 2016; Thompson et al. 2016). Moreover, how to ensure that the system protects the information it contains is a perceived challenge. Ballardini et al. (2018) addressed the IP rights in publicly available AM-enabled systems. Although the DI is not intended to be publicly available, a similar fear of leaked information is evident amongst the practitioners in our research. Thus, ensuring that data placed in the system remains protected is highly important to protect the organization.

5.2.3 Summarizing the Analysis for MRQ

To summarize we identified the following benefits and challenges:

- Benefits: reduced risk and cost, process optimization, further development, and increased competitiveness.
- Challenges: rules and regulations, change management, operations issues, strategy, profitability, system issues, and post-processing.

When investigating benefits and challenges a negativity bias may be present amongst respondents. The negativity bias is a psychological principle that means that negative events are more prominent than positive ones (Rozin & Royzman, 2001). Thus, it is not surprising to find a greater number of challenges than benefits. We do not place any importance on the number of themes found, as we do not involve quantitative elements in our research.

Within our findings, the codes involving human error might appear contradictory at first. We would argue that they are not. On the benefits side, the reduced manual steps naturally lead to

a reduced risk of human error. In contrast, the risk of human errors refers to the importance of feeding the DI the right information, as the DI cannot tell what is true or false.

From the challenges it becomes evident that there are trade-offs to consider and understand for successful DI implementation, to ultimately obtain the benefits identified. Lead time, capacity cost, and inventory cost all need to be calculated and weighed against each other. The lead time needs to be acceptable to the market and short enough to reduce physical inventory. However, the physical inventory should only be removed if the cost of the over-capacity needed to maintain an on-demand production is lower or equal to that of holding inventory. In both scenarios, we also strongly encourage decision-makers to conduct risk calculations. Reduction of physical inventory is reduced risk. However, promising a lead time in an on-demand scenario can also be considered a risk as there are often contracts to uphold.

Various components have different characteristics, they imply different things for the mentioned trade-offs. Components can require different post-processing activities and thus, has different lead times and capacity needs. Components can also be more or less costly to hold in inventory. Thus, to be able to make the calculations on trade-offs, an understanding of what should be included in a DI is necessary.

5.3 Analysis with Normann's Model

We use Normann's model (Normann, 2001), to further describe the DI concept and its digitalization. By introducing production-ready CAD files in the information storage instead of holding physical inventory, we have dematerialized (or digitized) the inventory. Since the inventory has been dematerialized and placed in the DI – it has become liquid, i.e., it is separated from the physical world and easier to move. Think about the difference in ease between moving a turbine component in real life versus sending it as a CAD file. Hence, there is a possibility to unbundle. The inventory activity is no longer held together in time, and not even necessarily place. As the turbine component is now digitized, the component can easily be printed whenever and wherever or even sent to another manufacturing unit for printing if desired. These steps mean that re-bundling the inventory becomes possible, by in theory printing on-demand. Parts can be printed only when needed, to create density. Creating density in the DI scenario means that components are printed first when ordered by a customer. Thereby the need for physical inventory would no longer be necessary. Through the DI value has been created for the

organization as costly physical inventory would not be needed. Instead, organizations only produce what is needed, when needed.

In the case of metal AM, however, one can question the unbundle-ability of a DI. Through practitioners, it becomes apparent that most metal-AM components require post-processing to be considered a finished product. The unbundle-ability refers to the separation of time and place. Since metal post-processing adds lead time and as some activities are outsourced, the time aspect of unbundle-ability is restricted. Additionally, to separate a DI from a specific place, each location would then have to have the capacity to not only print but also perform post-processing activities. As metal post-processing is complex and extensive, the movable aspect of unbundling becomes troublesome. Being able to unbundle is needed if a distributed approach is ever to be considered. Being able to re-bundle to create density might be hard through a metal DI, as the benefit of reducing physical inventory might be hindered if time or capacity restrains the value creation process. Thus, we can understand that a metal DI might not be suitable if the expectation is instantaneous value delivery. For this expectation other less complex production techniques or environments may be more suitable. However, if the lead time, capacity cost, and inventory cost trade-offs are considered, a metal DI may still be doable.

6. Conclusion & Discussion

In this section, the following will be presented and discussed: the study conclusion, the research's contribution to existing literature, the research's implications, the limitations of the research, and suggested further research.

6.1 Study Conclusion

This research has aimed to understand the DI concept through the lens of industrial practitioners and what potential benefits and challenges can be identified in the realization of DI for a large manufacturing organization. The data for this research was collected using qualitative group interviews and interviews.

Practitioners perceived the DI concept as a system with information storage capabilities that has an order to fulfillment possibility to allow for a make-to-order strategy, enabling simplified information sharing, and that needs to include information protection features.

The interest in implementing a DI was very high among the respondents, due to the perceived benefits that could be obtained following an implementation. Benefits identified included: reduced risk and cost, process optimization, further development, and increased competitiveness. However, despite the perceived benefits, several challenges stand in the way of a future realization of DI. Challenges included: rules and regulations, change management, operations issues, strategy, profitability, system issues, and post-processing. We could therefore conclude that there were seemingly more challenges in relation to DI than potential benefits. Some challenges may however be easier to overcome than others. The extent of the challenges may explain why DIs are not yet adopted by manufacturing organizations. Despite using a centralized approach for this research, we were able to note that most challenges and benefits could also be applied to an AM-enabled system using a decentralized approach. One example of this is the challenge of ensuring the performance of DI despite the necessity of post-processing activities. Moreover, the benefits and challenges identified and analyzed revealed a trade-off between lead time, capacity cost, and inventory cost. Understanding this trade-off, as well as knowing what components to include in a DI is a crucial step toward future adoption. To ultimately obtain the benefits observed.

We also applied Normann's model to our findings to explain how a DI would work and how a digitalized process such as DI could add value to organizations. Indicating the generalizability

of the DI concept. By combining the perceived benefits and challenges with Normann's model, we can understand that metal AM may currently not be suitable for a DI. As metal AM post-processing hinders the unbundle-ability, I.e., the ability to put the part together physically from its digitized state unrestricted by time and place. The time-consuming aspect of metal AM post-processing may hinder the reduction of physical inventory, one of the perceived benefits of DI adoption. If the physical inventory is not reduced, a higher density will not be achieved. Stressing the importance for organizations to consider the lead time, capacity cost, and inventory cost trade-offs before adopting a DI.

6.2 Theoretical Contribution

In recent years research on AM-enabled systems has increased in popularity. Most of that research has had a decentralized or distributed approach. Often disregarding the centralized approach. Yet for metal AM a decentralized or distributed approach is not yet possible due to challenges with AM, such as the post-processing necessity, as well as IP rights issues. Hence, we aimed at filling this gap, providing benefits and challenges of an AM-enabled system with a centralized and non-public approach.

With this research, we have contributed to the existing theoretical knowledge about the concept called DI. We have explored practitioners' conceptual perception of what a DI is, and what challenges and benefits the system holds. The challenges residing in different fields such as engineering, IT, and SCM indicates the difficulty in DI adoption and may explain why the concept has not yet been widely adopted.

6.3 Implications

The findings of this research could be of interest to managers who contemplate adopting an AM-enabled DI. As the findings can provide a relatively quick overview of the potential benefits that could be obtained, and challenges to be considered. The findings could also aid in creating a roadmap for how to design and scope the AM-enabled system, and thus allow organizations to obtain the full potential of AM. The concept, benefits, and challenges discovered in this research can be of use to researchers looking to further investigate specific AM techniques and components to discover the most suitable combination in the realization of DI. Additionally, seeing as this research has brought up a broad range of benefits and challenges it also presents an opportunity for researchers and managers to do a close-up investigation on a

few selected aspects. E.g., a manager could calculate the cost of having over-capacity vs. inventory costs to determine the profitability of implementing a DI.

6.4 Limitations

Due to our epistemological position, we acknowledge that there is a risk of bias when interpreting the qualitative interview data obtained from respondents. Moreover, our respondents' department belonging was not equally represented. E.g., there was only one respondent available from the IT department. This could affect the findings of this research since different perspectives were not equally represented. The sampling strategy also targeted individuals working within the AM part of the case company thus, respondents could be biased towards having a strong belief in AMs potential. Additionally, the data was collected in Swedish, but the thesis is written in English, the linguistic differences could have impeded the results. Moreover, a multiple case study could have been beneficial to increase the generalizability/transferability of this research. However, due to companies' belief in AM as a competitive advantage a multiple case study could have hindered the trust instilled between us as researchers and the company/s. Due to company internal covid-restrictions, we were not able to conduct larger face-to-face meetings and had to conduct single and two people interview instead.

A limitation to this research is the possible negativity bias present amongst respondents (Rozin & Royzman, 2001). The negativity bias means that it may be easier for respondents to see potential challenges rather than benefits. This means that there is a possibility that there are more benefits than presented in this research, and that the challenges identified might be exaggerated.

Throughout this research, we disclose numerous differences in production techniques, materials, and production strategies. The variations provide context and are expected to influence the benefits and challenges. Previous research does often not disclose these variations but rather uses AM as an umbrella term. When interpreting previous knowledge concerning benefits and challenges related to AM it is thus hard to make an accurate connection to correct contexts. The lack of disclosure on variations in previous research has limited our ability to accurately assess benefits and challenges said to affect AM or AM-enabled systems.

6.5 Further Research

Since AM, as well as AM-enabled systems such as DI, is relatively new several further research avenues could be suggested. We will however only present the avenues we see as most important to increase knowledge about. Technical research about the metal AM process is needed to better understand the process and to make it a more reliable manufacturing method. Technical research on how to design for metal AM is also necessary with the objective to reduce or eliminate the post-processing necessity.

Moreover, the cost of having over-capacity versus the cost savings of reduced physical inventory needs to be contrasted to determine the DI's feasibility from a profitability perspective. Models for such calculations could be beneficial for decision-makers and would preferably also include acceptable lead time considerations. To be able to calculate these trade-offs future research regarding spare parts characteristics suitable for inclusion in a DI is needed, as well as suggested selection methods.

In fact, another research avenue initially suggested by us and SE was investigating what components to include in a DI to reach the best effect. To do this we first had to establish what could or should be produced with AM. Proving difficult as product data was unavailable. Something Knofius et al. (2016) also found to be challenging. To determine what components to include in a DI, we must first know what to produce with AM. As the DI is AM-enabled. We hereby, want to stress the importance of identifying characteristics and methodologies to determine AM and DI suitability. Knowing what components to include was also expressed as a challenge by practitioners in this research.

The identified benefits and challenges in this research could also benefit from being researched quantitatively over a greater number of respondents from different sized companies, industries, or countries. Previous research and our findings link the DI concept to AM production. However, further research could investigate the possibilities of coupling DI with other CM methods. Considering that the application of an AM-enabled DI in this example is applied to SLM, future research could uncover the benefits and challenges with DI enabled by other AM techniques. More specifically, we found that a metal DI might not be suitable. However, plastic AM is considered mature (Lezama-Nicolás et al., 2018) and future research investigating plastic DI's potential would thus be suitable.

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Appendices

Appendix 1. Interview Guide for SRQ

- What department do you belong to?
- With your own words can you describe what a digital warehouse should entail from an internal perspective?
- How would it work in practice? Walk us through the process as you see it?
- In the realization of this type of system, what departments would need access to it?

Appendix 2. Digital Inventory Concept Information

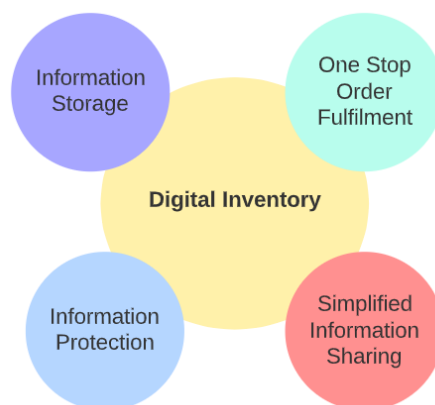
The AM-enabled Digital Inventory concept

We base our development of a Digital Inventory (DI) system on previous literature. Briefly, they define it as an alternative to physical storage where the components are stored digitally in the form of CAD files as opposed to storing them in a physical warehouse. Additive manufacturing (AM) can facilitate the shift towards DI due to AM's ability to manufacture directly from a digital design. We used this as our foundation to further develop the AM-enabled DI concept.

By AM-enabled we mean that this system/platform should be implemented in the AM workshop at Siemens Energy Finspång. The components that are aimed to be stored/manufactured using DI are therefore components produced using AM. Moreover, for our master thesis, we look at DI from a centralized point of view. Meaning that the production will take place on-site in Finspång. Moreover, we have delimited our thesis to DI for internal use.

In this paper, we present our conceptualization of the AM-enabled DI for Siemens Energy. The concept has been brought out by thematically analyzing qualitative data sets which we collected from interviews with Siemens Energy employees. In previous interviews, we explored the DI concept and what it should entail. To provide you with a context for our group interview where we will talk about benefits and challenges please see below.

From our findings, we have identified 4 major cornerstones in the realization of an AM-enabled DI for Siemens energy. Information storage, information protection, one-stop order fulfillment, and simplified information sharing.



Information storage

Regarding the information storage, it is firstly important that the DI can store production-ready CAD files needed to produce the AM components. The storage of production-ready CAD files is one of the aspects that would allow for on-demand printing. Since the printing would occur based on these CAD files, it is important to ensure the quality of the CAD files stored in the system. To ensure information quality the DI platform should therefore be connected to current pools of information (such as PLM and SAP etc.).

One-stop order fulfillment

The one-stop order fulfillment would work to enable on-demand production. In the DI platform, one should be able to place orders. The platform needs to be able to accommodate orders to trigger the demand. The on-demand production is then facilitated by the production ready CAD files already in the system. Meaning that the customer order point is moved to the end of the supply chain. Moreover, when placing orders, one needs to be able to see the lead time of the part being ordered. To accommodate this, the DI would have to be connected to production planning.

Simplified information sharing

The DI platform would work as an information sharing platform as it would enable the sharing of information between different departments and individuals (think about being able to see the lead time for example). To perform as a useful information sharing platform and make the information more accessible the DI platform would have to be designed in a user-friendly way.

Information protection

Information protection is another important aspect that will be included. One should be able to limit the access certain actors have to certain information to ensure information security. Moreover, information protection applications should be installed to ensure that all information that is stored in the DI is safe.

Appendix 3. Group Interview Guide for MRQ

Before the interviews could start the respondents were reminded of the DI concept as derived from the previous round of interviews. We asked the respondents to keep the description of a DI in mind when answering the questions, as it sets the context of our research. We also reminded the respondents that there are no right or wrong answers, as we were simply interested in the respondents' thoughts, ideas, and opinions.

The reminder provided to the respondents regarding the DI was as follows:

- The DI concept started from previous research and was further developed through a previous round of interviews with respondents from the case company.
- We're looking at a centralized production and a DI for internal use.
- Through the interviews, we identified four “cornerstones” that a DI needs to entail to work.
- The “cornerstones” are:
 - **Information storage** – containing production-ready CAD files. With great emphasis on the CAD files being production ready as this is what will allow for an on-demand process. As the printing happens based on these CAD files it is important to ensure the information quality of the files.
 - **One-stop order fulfillment** – information storage on its own does not enable an on-demand process, we also need a starting point I.e., a possibility to place or process orders in a DI. When placing an order, knowing the lead time is preferred. Thus, we need the DI to be connected to production planning.
 - **Simplified information sharing** – the DI would work as an information-sharing platform. Since we are sharing information between various departments without having to email.
 - **Information protection** – when sharing information like this, we also need to think about how to protect that information. Certain actors should not be able to access all information etc. Since you already have various information protection functions in another system (PLM), the DI could be connected to PLM.

After the description of the DI had been provided; we asked the respondents if any additional information was needed to understand the concept. When necessary, we provided further

explanations and background information on a DI, to enable the respondents to discuss related potential benefits and challenges.

- *Is this enough information for you to understand the concept? Do we need to fill you in on something more?*
- What department do you belong to?
- How would you describe that the realization of this system could be helpful or challenging for your company?
- What is your perception of the value of digitalization?
- What potential benefits do you expect from an AM-enabled DI?
 - What benefits do you expect in terms of financial flows?
 - What benefits do you expect in terms of material flows?
 - What benefits do you expect in terms of information flows?
- What are your greatest challenges with AM today?
- What potential challenges do you see in the realization of an AM-enabled DI?
 - What challenges do you expect in terms of financial flows?
 - What challenges do you expect in terms of material flows?
 - What challenges do you expect in terms of information flows?
- For the DI concept to work on-demand do you see the need for post-processing as a hinder or can components that require post-processing be included in this concept? Please explain.
- Do you see that it is possible to introduce the DI concept now, in the near future, or never – please motivate!

Appendix 4. Visualization of the Thematic Analysis for SRQ

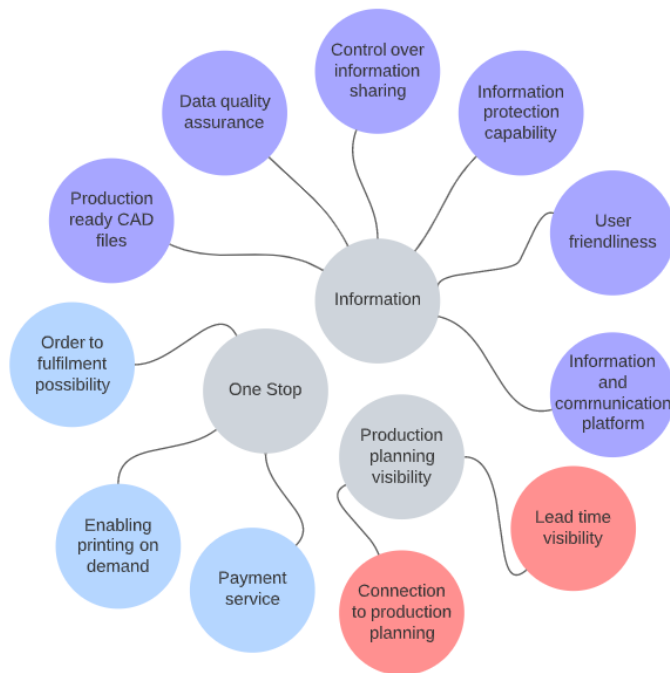
Step 1. *Familiarizing yourself with your data*

- Transcribing
- Reading thorough the transcriptions

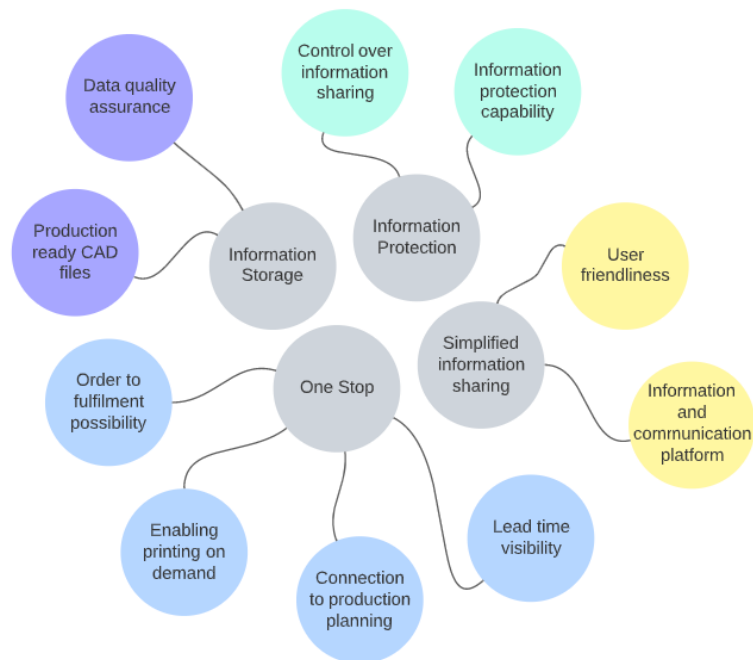
Step 2. *Generating Initial Codes*

Respondent	Data Extract	Coded For
E	A DI, instead of having it [the part] on an actual shelf, we have it easily accessible and specified to allow us to produce quickly.	Production ready CAD files
G	It's not really an inventory, it's actually about being able to shorten everything. To be able to produce a component make to order.	Enabling printing on-demand

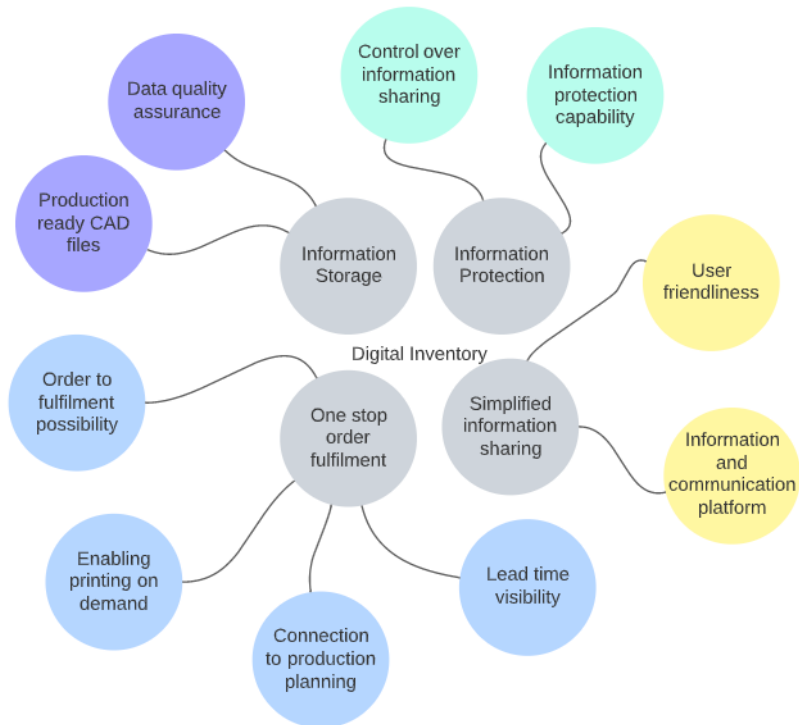
Step 3. Searching for themes



Step 4. Reviewing the themes



Step 5. Defining and naming themes



Appendix 5. Visualization of the Thematic Analysis for MRQ - Benefits

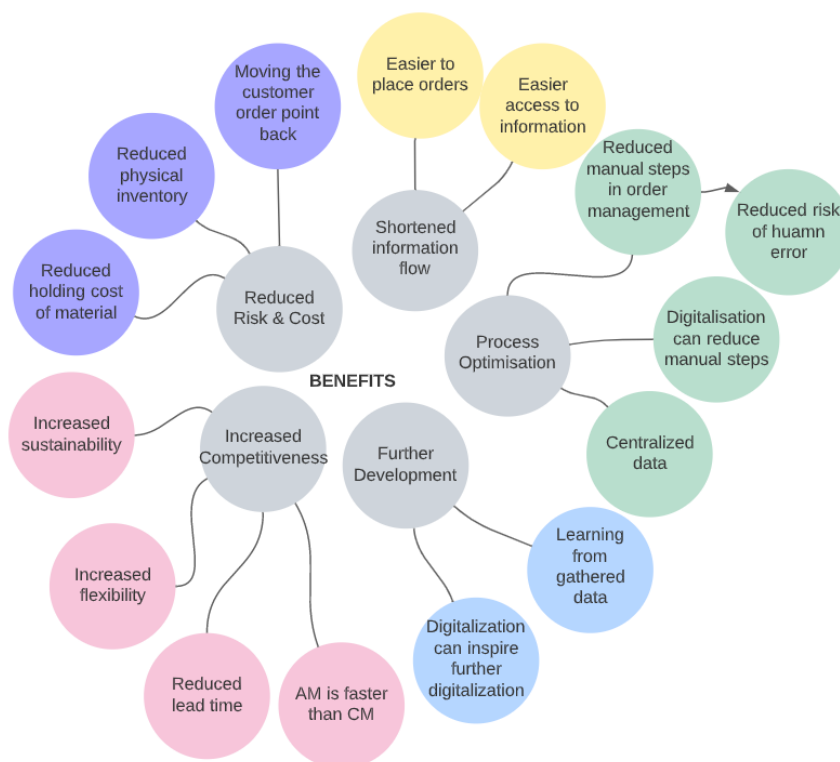
Step 1. Familiarizing yourself with your data

- Transcribing
- Reading thorough the transcriptions

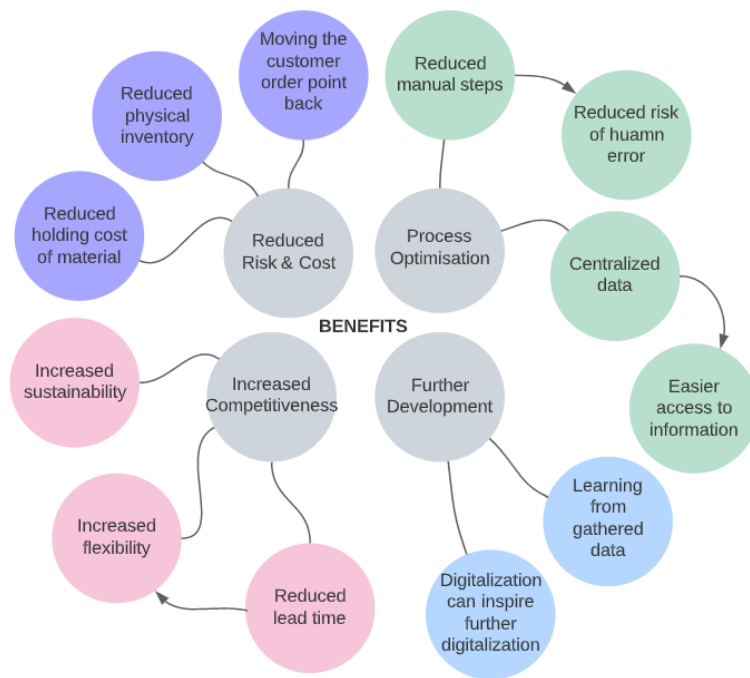
Step 2. Generating Initial Codes

Respondent	Data Extract	Coded For
6	If fewer people are involved, then the risk of errors in handling is reduced.	Reduced risk of human error
18	We wouldn't have to buffer anything physically, so without tying up capital we could meet the customers' demand.	Reduced physical inventory

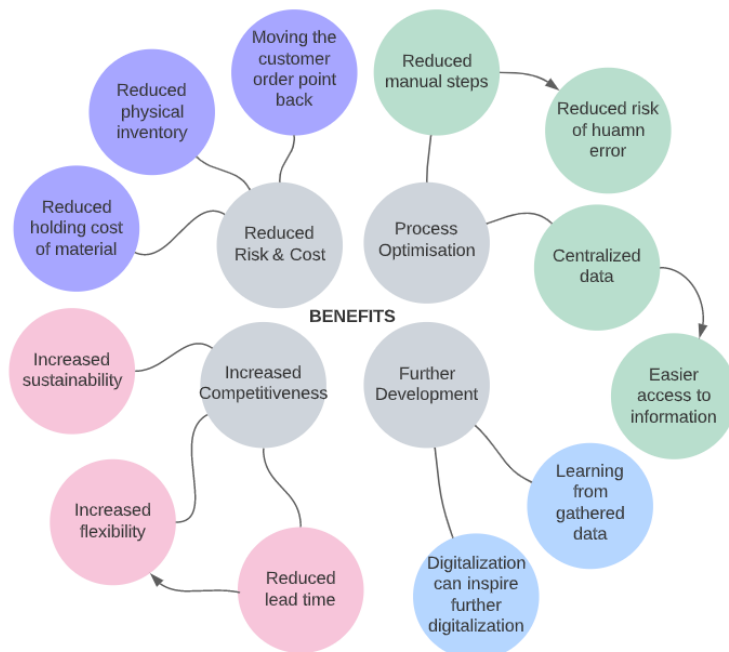
Step 3. Searching for themes



Step 4. Reviewing the themes



Step 5. Defining and naming themes



Appendix 6. Visualization of the Thematic Analysis for MRQ – Challenges

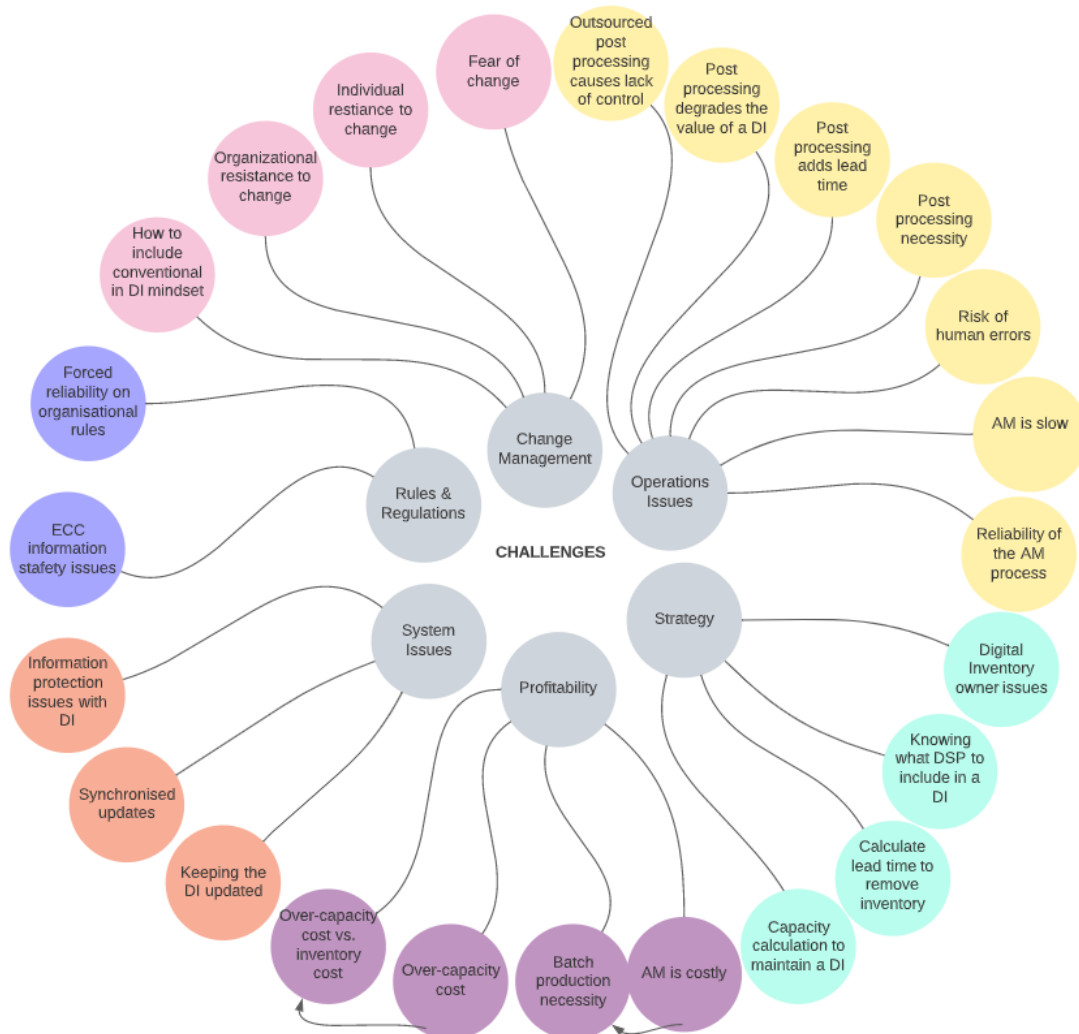
Step 1. *Familiarizing yourself with your data*

- Transcribing
- Reading thorough the transcriptions

Step 2. *Generating Initial Codes*

Respondent	Data Extract	Coded For
8	The lead time is quite long. The printing is fast compared to conventional methods but the post-processing is rather lengthy so we already have a lot of development to do for it to be as fast as we would like it. We need to reduce the lead time to be faster.	Post-Processing degrades the value of a DI
4	Our biggest obstacle from my perspective is the quality in our components. We are not in full control of our printed components just yet. It may differ between different printers in the spread of the powder. This aspect makes me especially nervous when printing new components.	Reliability of the AM process

Step 3. Searching for themes



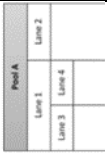









Step 4. Reviewing the themes



Step 5. Defining and naming themes



Appendix 7. Process Map Symbols

Symbol	Name	Description
	Swimlane	Swim lanes are used to organize aspects of a process map. They visually group aspects into lanes.
	Message flow	Represents information shared.
	Sequence flow	Connects objects in a sequential flow.
	Start Event	Signals the first step of a process.
	Intermediate Event	Signals event that can start or obtain information.
	End Event	Signals the end of a process.
	Data Storage	Signals the ability to access or store data associated with the process.
	Task	An activity that occurs in the process.
	Gateway	Often models decisions in a process.
	Data Object	Information sent in the process. We use it to depict digital information and communication.