University of Stavanger

KRISTIAN BANG-OLSEN (9013)

SUPERVISOR: ALI TÜRKYILMAZ

Assessing the influence of additive manufacturing and digital inventories on an Oil & Gas company's inventory management strategy

Master thesis, 2023

Master of Science in Business Administration

University of Stavanger Business School

Specialization: Leadership in a Digital Economy

Acknowledgements

I want to thank my supervisor Ali Türkyilmaz for his advice, guidance and help throughout the process of writing the thesis.

Also, I would like to thank Tor-Petter Egeland and Bjørn Kristensen from Vår Energi ASA for their contributions to shaping the thesis topic and providing contacts for the thesis. Further, thank you to the people who participated in the interviews.

Last but not least, I would sincerely like to thank my family and friends for their support throughout the semester.

Abstract

The oil and gas (O&G) industry is increasingly considering using additive manufactured (AM) for spare part management. As O&G companies seek to align their inventory management (IM) strategies, adopting digital inventories (DI) in combination with AM has emerged as a promising solution to current IM challenges in the industry. O&G operators may leverage AM and DI to reduce physical inventories, supply chain risk, inventory-related costs and lead times. However, approaches that describe how companies may implement the DI in operations and existing IM strategies are lacking. As such, this thesis will investigate how Norwegian O&G operators may implement DI to existing IM strategies.

Seven companies with experience with AM and currently participate in a DI ecosystem have been interviewed as part of the research for the thesis. The aim of the interviews was to explore the current challenges, best practices, and essential aspects for enabling the successful implementation of DIs. The interview findings are compared against relevant literature to understand the DI ecosystem comprehensively.

Key challenges in the ecosystem are unsuitable procurement processes, lack of commercial models, AM spare part (SP) qualification and a lack of demand for AM projects. ERP integration and assessments of AM suitability for stored SP are discussed as key enablers of DI implementation. The benefits and challenges associated with ERP integration will be discussed, thereby providing insight towards how O&G companies may utilise existing ERP systems to maximise the value of DI. A set of frameworks for identifying SP with characteristics suitable for AM is presented. The frameworks may be used to reduce physical inventories. Two decision models visualising critical decisions and stages for a SP ordered through a DI are presented. The first decision model considers decisions and stages for a given SP ordered through a DI. The second model may be adopted by O&G operators aiming to reduce physical inventories.

In conclusion, the thesis's main contribution is expanding knowledge of implementing DI as a part of IM strategies for Norwegian O&G operators. The findings highlight a need to address current procurement processes and develop attractive commercial models for all actors in the DI ecosystem. ERP integration and assessment of stored SP suitable for AM are identified as essential enablers of DI implementation.

Sammendrag

Olje- og gassindustrien (O&G) vurderer i økende grad å bruke additiv produksjon (AM) for reservedeler. Ettersom O&G-selskaper søker å samordne sine lagerstyrings strategier, har bruk av digitale varelager (DI) i kombinasjon med AM dukket opp som en lovende løsning på aktuelle -utfordringer i bransjen. O&G-operatører kan utnytte AM og DI for å redusere fysiske varelagre, risiko i forsyningskjeden, lagerrelaterte kostnader og ledetid. Men det finnes i liten grad tilnærminger som beskriver hvordan bedrifter kan implementere DI med eksisterende lagerstyrings strategier. Derfor vil denne masteroppgaven undersøke hvordan norske O&G-operatører kan implementere DI til eksisterende lagerstyringsstrategier.

Syv virksomheter med erfaring med AM og som deltar i et DI økosystem har blitt intervjuet som en del av forskningen til oppgaven. Hovedmålet med intervjuene var å utforske dagens utfordringer, beste praksis og viktige aspekter knyttet opp mot implementering av DI. Funnene fra intervjuer sammenlignes med relevant litteratur for å gi en helhetlig forståelse av DI-økosystemet.

Sentrale utfordringer i økosystemet er uegnede anskaffelsesprosesser, mangel på kommersielle modeller, AM reservedel kvalifisering og manglende etterspørsel etter AM prosjekter. ERP-integrasjon og vurdering av AM-egnethet for fyreservedeler lagret i varelager presenteres som sentrale faktorer for å muliggjøre DI-implementering. Fordelene og utfordringene knyttet til ERP-integrasjon vil bli diskutert, og gir derved innsikt i hvordan O&G-selskaper kan utnytte eksisterende ERP-systemer for å maksimere verdien av DI. Et sett med rammeverk for å identifisere reservedeler med egenskaper som er egnet for AM presenteres. Rammene kan brukes til å redusere fysiske varelagre. To beslutningsmodeller som visualiserer kritiske beslutninger og stadier for en reservedel bestilt gjennom et DI presenteres. Den første beslutningsmodellen vurderer beslutninger og stadier for en gitt reservedel bestilt gjennom en DI. Den andre modellen kan tas i bruk av O&G-operatører med sikte på å redusere fysiske lagre.

Avslutningsvis er oppgavens hoved bidrag å utvide kunnskapen om implementering av DI som en del av IM-strategier for norske O&G-operatører. Funnene synliggjør et behov for å adressere nåværende anskaffelsesprosesser og utvikle attraktive kommersielle modeller for alle aktører i DI-økosystemet. ERP-integrasjon og kartlegging av lagrede reservedeler egnet for AM er identifisert som nøkkel drivere for DI-implementering.

Table of Contents

Table of figures

List of tables

Abbreviations

Additive Manufacturing	–	AM
Bill of Material	–	BOM
Computer-Aided Design	–	CAD
Conventional Manufacturing	–	CM
Digital Inventories	–	DI
Digital Spare Parts	–	DSP
Economic Order Quantity	–	EOQ
Enterprise Resource Planning	–	ERP
Green House Gasses	–	GHG
Inventory Management	–	IM
Intellectual Property	–	IP
Just-in-Time	–	JIT
Material Resource Planning	–	MRP
Oil and Gas	–	O&G
Original Equipment Manufacturer	–	OEM
Spare Part	–	SP
Supply Chain Management	–	SCM

1 Introduction

The concept of additive-manufactured spare parts (SP) has received increasing attention due to its potential to disrupt companies' supply chains (SC) (Arbabian, 2022; Chekurov et al., 2021). Also, the concept of using digital inventories (DI) containing spare part CAD files intended for additive manufacturing (AM) has gained traction due to its promising implications for companies' supply chains. Instead of storing SPs in physical inventories, SPs are stored in DI and printed on-demand (Chekurov, Metsä-Kortelainen, Salmi, Roda, & Jussila, 2018; Khajavi, Salmi, & Holmström, 2020). AM has the potential to reduce lead time for certain types of SPs significantly (Chiu & Lin, 2016). Further, since SP are stored in a DI, files can be sent digitally to AM printers close to the origin of demand (De La Torre, Espinosa, & Domínguez, 2016). As such, combining AM and DI can potentially reduce supply chain complexity and risk (Rupp, Buck, Klink, Merkel, & Harrison, 2022). From an inventory management (IM) perspective, AM can potentially reduce the need to store SPs in physical inventories (Mecheter, Pokharel, & Tarlochan, 2022).

Despite the proposed benefits of AM, the oil and gas (O&G) industry has been slow compared to other industries, such as automotive and aviation, to embrace the technology (Sireesha et al., 2018). It is expected that the O&G industry will see the most significant benefits of AM through its impact on their SC (Sireesha et al., 2018), mainly due to the extended use of capital SPs and often long lead times for SPs (Mecheter et al., 2022). Using AM and DI for on-demand manufacturing close to the origin of demand is highly relevant for the O&G industry as assets are often located in remote areas (Barbosa, Gouvea, Martins, Belmonte, & Wanderley, 2022; Chandima Ratnayake, Keprate, & Wdowik, 2019). Knofius, van Der Heijden, & Zijm, (2016) noted that SP management is increasingly complicated when assets are distributed far away from inventories, large variety in SP types, and when SPs are expensive.

Vår Energi ASA is a Norwegian O&G operator. They have started to realise the potential of AM and have engaged in a DI joint industry project (JIP) with six other O&G operators and a software company to support the creation and use of a DI. Vår Energi ASA has little AM experience compared to other O&G operators but is keen to catch up. One of the aspects they are interested in learning more about is how they may utilise DI as a part of their supply chain

(SC) and IM strategies. At the end of 2022, Vår Energi ASA's inventory was valued at 2.48 billion NOK (Vår Energi ASA, 2022). During conversations with representatives from Vår Energi ASA, it was revealed that they estimate that 80% of the inventory will never be used. The company is interested in AM and DI due to its potential to enable on-demand SP manufacturing and reductions in physical inventory.

In general, while developing the thesis' topic and research questions (RQ), several gaps in the academic literature concerning DI, DI ecosystems and the implications for companies' SC and IM strategies were discovered. For example, storing AM files in DI has not yet gained much attention in the relevant literature (Lastra, Pereira, Díaz-Cacho, Acevedo, & Collazo, 2022). Also, most of the proposed benefits of DI being discussed in the academic literature are based on theoretical benefits (Chekurov et al., 2021). Due to the limited attention DI has yet to receive, calls have been made to gain insight from companies already using AM in their SC (Chekurov et al., 2018; Holmström, Partanen, Tuomi, & Walter, 2010). Further, few articles consider precisely what companies need to change in their SC to enable distributed manufacturing using AM (Khajavi, Partanen, & Holmström, 2014). The research gap also extends to descriptions and best practices concerning how DI ecosystems should be organised. To address the gaps in current academic research and Vår Energi ASAs wish for advice regarding how DI could be used as a part of their IM strategy, the following RQs were derived:

RQ 1: How should DI ecosystems be organised to fully capture AM's SC benefits?

RQ 2: Which IM related challenges are companies engaged in DI ecosystems currently facing?

RQ 3: How to implement a DI as a part of an O&G operator's IM strategy?

RQ 1 aims to uncover how companies currently engaged in DI ecosystems perceive their roles and how the DI ecosystem should be organised. RQ2 will reveal current challenges in the DI ecosystem relevant from an IM perspective. RQ 3 aims to explore specific aspects relevant to further implementing and using DI as part of an IM strategy. The RQs will be addressed using information obtained from interviews with companies suggested by Vår Energi ASA. The information obtained through interviews will be discussed, considering relevant academic literature. Further, actions identified as critical for enabling the utilisation of DI for on-demand manufacturing and inventory reduction will be presented.

Hereafter the thesis is structured as follows: Chapter 2 is literature review related topics such as IM, AM and DI. Chapter 3 will present the research design and methodology used to address the RQs and the scope of the thesis. Chapter 4 will discuss findings from interviews and academic literature. The findings will subsequently be discussed in light of the RQs, and strategic advice will be presented. Finally, Chapter 5 concludes the thesis.

2 Literature Review

The literature review is divided into three sections. Section 2.1 introduces inventory management strategy as a concept and various IM approaches. Section 2.2 reviews relevant literature regarding AM in the context of IM. Finally, section 2.3 is a review of existing literature concerning DIs and digital SPs.

2.1 Inventory Management

IM as a concept has several definitions. Priniotakis & Argyropoulos, (2018) defined inventory management as "the process of monitoring and controlling inventory level and ensuring adequate replenishment in order to meet customer demand" (p. 1). Singh & Verma, (2018) provide a slightly more specific definition, stating that IM is "the continuing process of planning, organising and controlling inventory that aims at minimising the investment in inventory while balancing supply and demand" (p. 2). The IM concept is further specified by Singh & Verma, (2018) as they claim considerations such as lead time, asset management, price and inventory forecasting and replenishment all lie within the scope of IM. Other researchers, such as Aro-Gordon & Gupte, (2016) and Akindipe, (2014), include procurement, transportation and disposal as key considerations within the scope of IM. Thus, IM can be said to consider activities related to planning, obtaining, storing, deploying input and output to support a company's operations.

Inventory is a term used to describe the item(s) a company holds in their stock intended to be used or sold. The items are usually considered a buffer between operational demand and supply (Williams & Tokar, 2008). Typical examples of items stored in inventories are raw materials, partly finished goods, finished goods or SPs (Aro-Gordon & Gupte, 2016). According to Tom Jose, Jayakumar, & Sijo, (2013), inventories are often a company's most important asset and consume significant working capital. Also, inventories are necessary for companies to store items they will use in their operations at some point (Oluwaseyi, Onifade, & Odeyinka, 2017). Thus, the challenge of finding an optimal inventory level lies at the heart of IM (Chebet & Kitheka, 2019). By not having necessary stock in its inventory, a business may face considerable operational issues, but by having too much stock, the company sacrifices working capital that may have been more efficiently utilised elsewhere in the business (Oluwaseyi et al., 2017; Priniotakis & Argyropoulos, 2018). Companies use material resource planning

(MRP) and enterprise resource planning (ERP) systems to manage and plan activities, procurement and items stored in inventory (Kortabarria, Apaolaza, Lizarralde, & Amorrortu, 2018).

Approaches aiming to manage an efficient combination of inventory stock and service level may be classified as push- or pull approaches (Esmaeilian, Behdad, & Wang, 2016). According to Puchkova, Le Romancer, & McFarlane, (2016), the push approach represents the traditional way of organising inventories. In a push approach to IM, one aims to store parts in the inventory before a demand arises (Yang, Cai, & Chen, 2018). Typically, MRP systems are based on push approaches where production schedules, inventory data and bill of material (BOM) are used in an attempt to forecast future demand (Kortabarria et al., 2018). Further, push approaches aim to minimise lead time and be well-equipped to handle the demand for items stored in the inventory (L. Liu, Xu, & Zhu, 2020). However, the push approach may result in high inventory costs, low SP turnover and increased rates of obsolescence (Poles, 2013). In contrast, the more recently popular pull approach aims to procure parts or inventory after a demand has arisen and have parts arrive at the origin of demand just as needed (L. Liu et al., 2020). This approach can reduce required inventory levels significantly and, subsequently, inventory costs while increasing efficiency (Bortolotti, Danese, & Romano, 2013). Table 1 summarises the key differences between pull and push-based inventory management systems.

Table 1

Differences Between Push and Pull Inventory Approaches

Aspect	Pull-Based Inventory	Push-Based Inventory	Source
Approach	Based on actual customer demand.	Based on projected demand.	(C. Li & Scheller-Wolf, 2011; Yang et al., 2018)
Trigger for Replenishment	Replenishment is triggered by customer demand.	Replenishment is based on forecasted or planned demand.	(Puchkova et al., 2016)
Flexibility	More flexible and adaptable to demand fluctuations. Can lead to stockouts if demand is unpredictable	Allows for efficient production planning. May result in excess inventory if forecasts are inaccurate	(Bortolotti et al., 2013; L. Liu et al., 2020)
Customer Satisfaction	High potential for meeting customer demand accurately and reducing stockouts. Potential for stockouts if demand is underestimated	Potential for stockouts or excess inventory leading to customer dissatisfaction.	(L. Liu et al., 2020; Puchkova et al., 2016)
Inventory Holding Costs	Potential for reduced holding costs due to lower inventory levels. May require more frequent replenishment, increasing ordering costs	May result in higher holding costs due to larger inventory quantities	(Puchkova et al., 2016)
Supply Chain Responsiveness	Enables quicker response to changes in demand or market conditions	May have longer lead times and response times to changes	(L. Liu et al., 2020)
Risk Mitigation	Reduced risk of inventory obsolescence or excess stock	Higher risk of inventory obsolescence or excess stock	(Puchkova et al., 2016)

Note. Summary of main differences between push and pull IM approaches.

The Just-in-Time (JIT) manufacturing philosophy has gained broad interest because of the numerous examples of companies experiencing significant improvements in terms of cost reductions and increases in operational efficiency (Nawanir, Kong Teong, & Norezam Othman, 2013). JIT manufacturing is a popular pull-oriented approach aiming for inventory deliveries just in time for a given production stage (Javadian Kootanaee, Babu, & Talari, 2013; Tom Jose et al., 2013). Related to IM, JIT implementation has the potential to significantly reduce waste, lead time, and inventory costs while also increasing SP quality (Rahman, Sharif, & Esa, 2013). However, aiming to receive deliveries just as they are needed require significant coordination efforts from the SCM and IM departments (Sundar, Balaji, & Kumar, 2014). As such, having ERP systems capable of accurately representing the status of operation, procurement and inventory at any given time gains are crucial (Daryl Powell, 2013).

Companies implement various IM methodologies and tools to balance the push and pull forces influencing their IM according to their needs (Chebet & Kitheka, 2019). For example, measures such as economic order quantity (EOQ) and economic order quantity (EPQ) are used to determine the optimal order quantity while minimising inventory holding and ordering costs (Pasandideh, Niaki, & Nia, 2011; Ziukov, 2015). Other methods related to managing inventories effectively are reorder point, quantity discounts and single- and fixed-period models. Reorder points determine the minimum number of items to be stored in an inventory based on projected demand. A replenishment order is issued if the number of items exceeds the set amount (Inegbedion, Eze, Asaleye, & Lawal, 2019). Quantity discounts are based on orders above a given threshold (Alfares & Ghaithan, 2016). Single-period models are often used in situations with uncertain demand and are used when an inventory is not replenished (Hnaien, Dolgui, & Wu, 2016). Contrarily, fixed-period or quantity models determine if an item should be re-stocked regardless of demand, aiming to balance inventory holding costs (Kostić, 2009).

2.2 Additive Manufacturing and Inventory Management

Additive manufacturing (AM), also known as 3D-printing, is a term used to describe a production process where material usually is joined layer upon layer from computer-aided design (CAD) models (Abdulhameed, Al-Ahmari, Ameen, & Mian, 2019; Mellor, Hao, & Zhang, 2014). By adding material it contrasts conventional manufacturing (CM) methods, such as subtractive manufacturing processes where the material is gradually removed (Khalid & Peng, 2021; Watson & Taminger, 2018). Subtractive manufacturing techniques such as milling, boring, turning and grinding are typical examples of subtractive manufacturing processes (Watson & Taminger, 2018). There are mainly three categories of AM production processes; liquid, solid, and powder-based. (Wong & Hernandez, 2012). Table 2 show an overview of the most common AM production processes (Abdulhameed et al., 2019; Bourell et al., 2017; Dilberoglu, Gharehpapagh, Yaman, & Dolen, 2017). Regardless of the AM production process, usually material is fed into a machine, layers are selectively melted or bonded togheter, and subsequently cooled (N. Li et al., 2019). AM enable the production of SPs in a range of various materials. Typical examples of usable materials are plastics, steel, various metals composites or -alloys (Dilberoglu et al., 2017; N. Li et al., 2019).

Table 2

Overview of most common AM production methods

AM method	Description
Material Extrusion	The molten material is deposited layer by layer
Vat Photo-polymerisation	Liquid photopolymer resin is selectively cured layer by layer using light.
Material Jetting	Material is deposited layer by layer.
Binder Jetting	A liquid binder is jetted onto layers of powdered material to bind the material together.
Powder Bed Fusion	Use of laser or electron beam to selectively melt layers of powdered material together
Direct Energy Deposition	Use of lasers or electron beams, molten material is added layer by layer.
Sheet Lamination	Material is added in thin layers upon layers using adhesives or heat.

Note. The most commonly used AM production methods. From Bourell, D. et al., (2017). Materials for additive manufacturing. *CIRP Annals*, *66*(2), 659–681. https://doi.org/10.1016/j.cirp.2017.05.009. From Dilberoglu, U. et al., (2017). The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manufacturing*, *11*, 545–554. https://doi.org/10.1016/j.promfg.2017.07.148.

AM was first developed as a manufacturing technique in the '80s and has been predominantly used for prototyping (Montero, Weber, Bleckmann, & Paetzold, 2020). However, technological developments have increasingly made AM an attractive manufacturing technique in various industries (Rayna & Striukova, 2016). Promises of reduced lead time, simpler supply chains (SC), production close to demand, easily adaptable design and reduced raw material usage are attractive traits for any company reliant on SPs in their operations (Chekurov et al., 2021). Additionally, compared to CM processes, AM parts can be made with more complex geometrical features than CM parts (Manogharan, Wysk, & Harrysson, 2016; Rupp et al., 2022). As such, AM has seen the most development in the aerospace and medical industries (Abdulhameed et al., 2019). Key factors driving the utilisation of AM in the aerospace industry include the ability to consolidate several parts into one part and the ability to create hollow parts, ultimately contributing to weight reduction (Togwe, Eveleigh, & Tanju, 2019). In the medical industry, three-dimensional scanning and AM have been used to print body parts replacements (Javaid & Haleem, 2018).

The increasing interest in AM can also be seen in the context of its potential to make IM more environmentally sustainable (Cardeal, Ferreira, Peças, Leite, & Ribeiro, 2022; Khalid & Peng, 2021). A key feature of AM is that scrap material can be recycled and transformed into raw material used to create new parts (Daniel Powell, Rennie, Geekie, & Burns, 2020). Additionally, AM is attractive for companies reliant on SPs because AM can be utilised to repair defective SPs and thus extend the lifetime and reduce the waste of valuable resources (Zanoni, Ashourpour, Bacchetti, Zanardini, & Perona, 2019). A defective part can be digitally scanned into a CAD file, which can be modified and repaired to a functional state (Wits, García, & Becker, 2016). In situations where SPs are hard to obtain, or SP production has been discontinued by the original equipment manufacturer (OEM), scanning and AM can be used to extend the lifetime of functional equipment which otherwise would have been replaced or scrapped (Montero et al., 2020; Zanoni et al., 2019). Other often-mentioned features of AM potentially contributing to more sustainable inventory practices is the ability to produce parts close to the demand origin and produce parts according to actual demand (Cestana, Pastore, Alfieri, & Matta, 2019).

However, several factors regulate how AM can be considered a more sustainable alternative to CM. For example, the processes involved in turning scrap into usable powder are highly toxic and energy-intensive (Ford & Despeisse, 2016). Also, Faludi, Van Sice, Shi, Bower, & Brooks, (2019) found that the method used to generate the electricity required to create AM raw materials heavily influence whether an AM part has a net negative footprint compared to a CM part. Moreover, AM as a production method is highly energy intensive, according to Cardeal, Ferreira, Peças, Leite, & Ribeiro, (2022). Lastly, in an comprehensive literature review studying the entire lifecycle of AM parts by Khalid & Peng (2021), they noted that the models and estimates used to determine AM SPs footprint vary considerably. Thus, any claim towards AM and sustainability must be considered cautiously.

Many of the key benefits associated with AM SPs over CM SPs are related to IM and supply chain management (SCM) (Montero et al., 2020). According to Araújo, Pacheco, & Costa, (2021), many of the production stages necessary for the production of CM parts are redundant in AM processes. As a result, AM facilitates rapid parts production and has the potential to reduce lead times significantly (Lastra et al., 2022; Westerweel, Basten, & van Houtum, 2018). Reduced lead time has significant implications for companies' IM strategies as more SPs can be produced just-in-time according to demand (Ford & Despeisse, 2016). Naghshineh & Carvalho (2022) highlighted AM SPs' potential to increase supply chain resilience (SCR). In a comprehensive literature review investigating the relationship between AM and SCR, features such as distributed production, design flexibility, automated production and increased potential to adjust production to demand as features increasing supply chain resilience. P. Liu, Huang, Mokasdar, Zhou, & Hou, (2014) found that AM has the potential to reduce the number of items kept as safety stock and slow-moving parts. Others, such as Knofius, van der Heijden, Sleptchenko, & Zijm, (2021) suggested that adopting dual sourcing policies utilising both CM and AM SPs could reduce the negative IM and SCM attributes of the respective manufacturing methods, and instead be used to complement each other. As such, the threats associated with over reliance on either AM or CM can be avoided.

Despite the potential IM improvements obtained by utilising AM SPs, several authors have noted various challenges related to the manufacturing technique. A commonly mentioned challenge AM currently face is being reliant on a limited selection of valuable materials (Ford & Despeisse, 2016). Although the number of materials available for use in AM is increasing, they note that any significant disruption to the production of AM raw materials serves as a potential production bottleneck. In a study modelling AM SP demand, Yuan Zhang, Jedeck, Yang, & Bai, (2019) concluded that AM is only a more economically beneficial production process than CM under specific conditions. Most notably, AM is preferable for physically smaller SPs produced in small production batches (Abdulhameed et al., 2019; Thomas, 2016). Additionally, Westerweel et al., (2018) found that the currently narrow scope of economically feasible production runs often ensures that investments in CM machines are more favourable.

2.3 Digital Inventories and Digital SPs

Traditionally, digitalisation concerning IM and SCM has focused on implementing technological advancements such as digital twin modelling, IoT, RFID tagging systems, automation using robots, and ERP systems to control better items stored in physical inventories (Attaran, 2020). However, for AM and SPs, the discourse refers to DI as a fully digital inventory consisting of digital CAD files (Verboeket & Krikke, 2019). As such, the latter definition of the concept of DI is the one that will be used in the thesis going forward. The CAD files stored in DIs are commonly called digital SPs (DSP) in literature (Chekurov et al., 2018). In a large study assessing the implementation of AM in industrial SCs, Chekurov et al., (2018) conducted group interviews with manufacturing experts and OEMs to identify DSP adoption issues. Based on relevant literature and results from interviews, they defined DSP as:

> A concept in which defective components are replaced by manufacturing SPs close to the location of need from 3D model data that are transferred by network with the main consequences of reducing repair time, delivery time and costs, emissions, and inventory. (Chekurov et al., 2018, p.9)

Several authors have suggested various ways adoption of DI and DSP could benefit IM strategies (Ballardini, Flores Ituarte, & Pei, 2018). First, because SPs are stored digitally, the SP can be updated at any time. In contrast, SPs stored in physical inventory may have to be sold at a loss or scrapped if revisions make old SPs obsolete (Holmström et al., 2010). According to Knofius et al., (2021), AM DSP also introduces the possibility of reducing the number of components in each part by allowing the merging of SP CAD files. Instead of several components making up one larger SP, all necessary features can be printed as one, reducing assembly complexity, manufacturing time, material and required inventory (Wits et al., 2016). Additionally, omitting the storage of physical SP reduce raw material consumption because SPs are printed as they are needed (Ott, Pascher, & Sihn, 2019). DSP also allows the instant sharing of files to locations closer to the demand origin, removing the need to transport physical SP over long distances (Rupp et al., 2022). This would reduce greenhouse gas (GHG) emissions and lead time when SP otherwise had to be transported long distances to reach their demand origin. (González-Varona et al., 2020).

The benefits associated with DI and DSP have also been suggested as enabling the transition towards a pull-based IM strategy (Rupp et al., 2022). The digital SPs can be printed as soon as a need is registered (Lastra et al., 2022). Also, as the production time related to printing the part and any necessary post-print work is typically known, the part is printed when it arrives just in time for it to be needed (Lastra et al., 2022). Thus, DI inventories reduce the need for extensive physical inventories as SPs are stored digitally, and parts are stored for a reduced amount of time in the end users' inventory before they are used (P. Liu et al., 2014; Ott et al., 2019).

However, currently, there are several challenges related to the utilisation of DI and DSP (Ballardini et al., 2018; Chaudhuri et al., 2021). According to Chekurov et al. (2018), adopting DI and DSP requires a comprehensive network of companies specialising in their own field. The network described by Chekurov et al. (2018) will, among others, need to include software companies, independent verifiers, AM SP producers, AM SP material providers and end users. Because AM as a manufacturing technique is still relatively new, it has to prove itself economically viable before widespread adoption can be expected (Lindemann, Reiher, Jahnke, & Koch, 2015). Furthermore, intellectual property (IP), piracy, commercial and legal worries contribute to hesitance towards DI and DSP adoption (Ford & Despeisse, 2016; Gupta, Tiwari, Bukkapatnam, & Karri, 2020).

Much attention has been paid to assessing how AM might influence companies' management of SPs and their inventories. Using DI to store AM CAD files digitally rather than in physical inventories is also gaining attention. The hypothesised benefits of on-demand manufacturing and reduced inventories because of AM and DIs are routinely mentioned in relevant academic literature. However, few articles address what actions a company should take to implement DIs as a part of its existing IM strategy. Also, there is a distinct lack of information concerning the status, opportunities, and barriers of using AM in relation to DIs. The next chapter will describe the methodology and research design used to investigate these gaps in the academic literature and address the RQs.

3 Methodology

This section will present the research methodology used answer the thesis' research questions. In the first section, the thesis research design will be explained. The second section will present the data samples. Section three discuss how primary data was collected through interviews and secondary data from academic literature. In the fourth section, the topics of validity and reliability will be addressed. Finally, section five will describe how the interview participants' privacy rights and other ethical considerations were maintained.

3.1 Research Design

The motivation and background for the thesis stem from Vår Energi ASA's mentioned interest in AM and DI. Through analysing academic literature and discussions with Vår Energi ASA, it was decided that the thesis would explore current challenges and opportunities related to DIs in the Norwegian O&G industry. Also, the thesis also aimed at exploring how Norwegian O&G operators may proceed in implementing DIs to existing IM strategies. Thus, the thesis aims to provide Vår Energi ASA with actionable strategic advice regarding best practices and how they should move forward using AM and DI. Additionally, the thesis aims to contribute to closing certain knowledge gaps in academic literature. The following RQs were developed based on the mentioned literature search and discussion with Vår Energi ASA:

RQ 1: How should DI ecosystems be organised to fully capture AM's SC benefits?

RQ 2: Which IM related challenges are companies engaged in DI ecosystems currently facing?

RQ 3: How to implement a DI as a part of an O&G operator's IM strategy?

A qualitative research design has been used as the aim of the thesis is to explore and understand the current challenges and opportunities regarding AM and DI in the Norwegian O&G industry. Semi-structured interviews were used to collect data from people in relevant companies. A semi-structured interview involves asking participants open-ended questions and using follow-up questions (Kallio, Pietilä, Johnson, & Kangasniemi, 2016). Additionally, this interview format is characterised by using a pre-determined set of topics or questions while maintaining the freedom to explore other questions that may arise during the interview (Kallio et al., 2016).

Also, secondary data was obtained through academic articles relevant to the scope of the thesis. The purpose of obtaining data from interviews combined with academic articles is two-fold. First, obtain real-world information on relevant subjects from practitioners, and second, compare the findings in academic literature with the data gathered from participants. This research method, called triangulation, is used to cross-check findings from different data sources (Carter, Bryant-Lukosius, DiCenso, Blythe, & Neville, 2014). The research design has been externally validated by the Norwegian Centre for Research Data (NSD). Figure 1 summarises the methodological process used in the thesis:

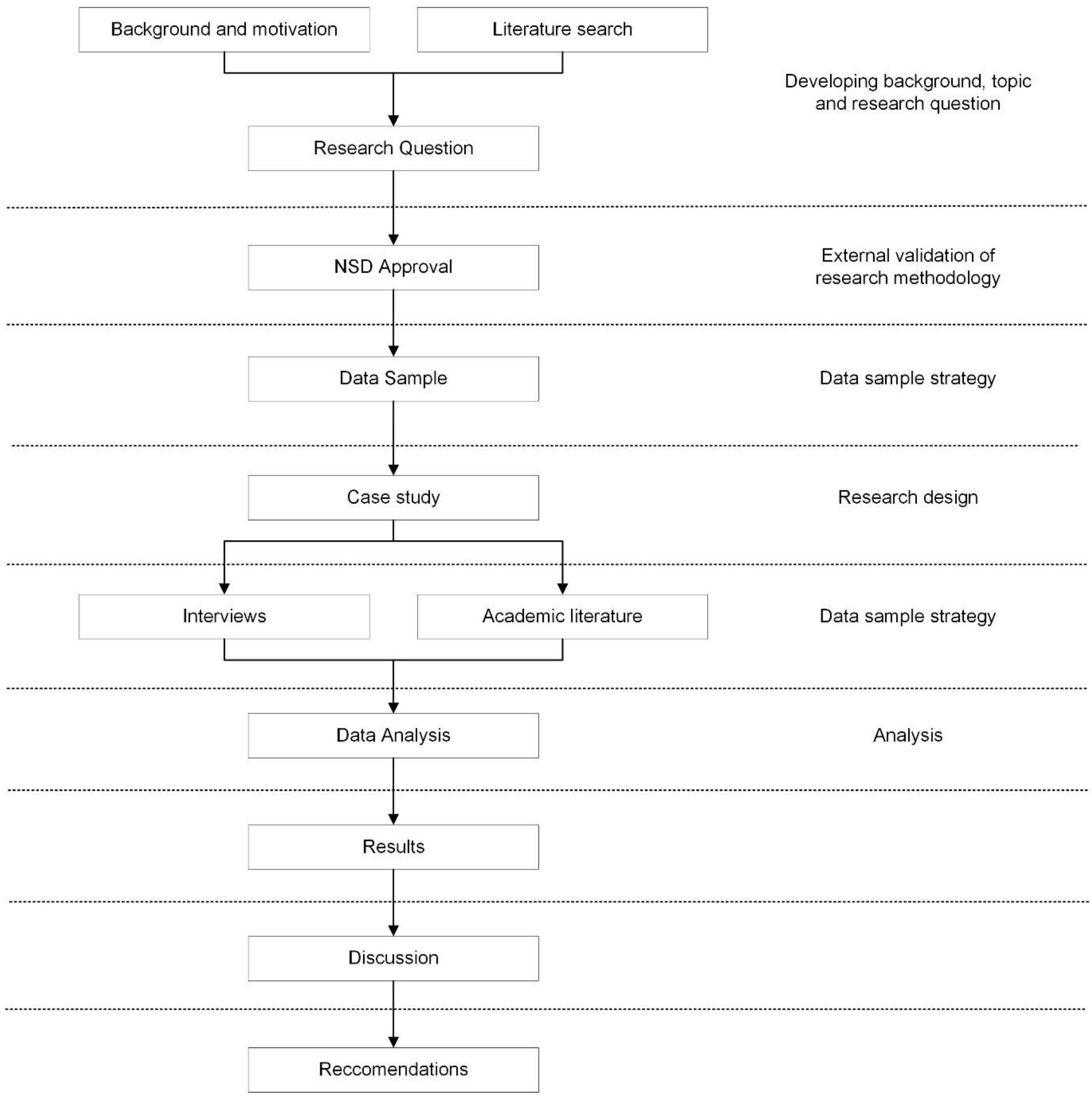

Figure 1. Thesis' research process.

3.2 Interview Participant Sampling strategy

The companies selected for interviews are companies Vår Energi ASA identified as relevant stakeholders because of their involvement in DI and AM in the Norwegian O&G industry. The companies identified by Vår Energi ASA occupy various roles in a AM value chain. Thus, the sampling strategy could be considered as a purposive sampling strategy. In a purposive sampling strategy, participants are selected based on criteria or characteristics relevant to the research (Andrade, 2021; Robinson, 2014). While purposive sampling as a sampling method has certain limitations (Andrade, 2021), which will be discussed in section 3.6 limitations, the method was deemed acceptable because of the specific level of knowledge or experience required to provide valuable data (Campbell et al., 2020). In this case, the participants would ideally have experience with AM and be familiar with DI and the Norwegian O&G industry. All of the companies who have participated in the thesis meet these criteria.

The companies identified by Vår Energi ASA all have experience with AM to a varying degree. Some companies have already gained extensive knowledge and experience in producing AM parts or providing services relevant to AM. However, one company (Company 4 in Table 3) has yet to produce any AM parts but is currently training employees and will receive their first printer in the summer of 2023. Although the company has little experience in the production of AM parts compared to some of the others in the sample, they were still included because; 1) The company is newly founded, and it was judged as relevant to examine how a start-up approaches AM in relation to DIs. In contrast, most of the other companies in the sample are either large international companies or subsidiaries of larger industrial companies. 2) The geographic location of Company 4. The company is located in the northern part of Norway, while the rest are in the southern part of Norway. Because of the difference in geographic location, including Company 4 was considered relevant.

The aim of interviewing companies providing different products or services was to establish a holistic picture of the status, challenges, opportunities and enablers faced by companies connected to AM and DIs. The sample includes a company specialising in AM part printing, a company providing scanning and digitalisation services, an OEM of various pump-related parts, a software company that manages an AM DI, a company that provides verification and certification services, and finally, a O&G operator. Table 3 show a summary of the companies, their relationship with AM and DI and the respective people who participated:

Table 3

Overview of Interviewed Companies and Company Representatives

Company No.	Role in the DI and AM Ecosystem	Company Experience with AM	Participant Position in Company	Participant Experience with AM
Company 1	Software company owning and responsible for maintaining a DI.	Established in 2021. Daughter company of company with experience in AM since 2016	Project manager	Project manager for the DI collaboration project
Company 2	Scanning and digitalisation of SPs	Twenty years of experience in technology relevant to part scanning.	Leader for SP digitalisation department	Material experience from university.
Company 3	3D CAD services and 3D printing of parts	Has provided modelling services and prints AM parts	CEO	15 years
Company 4	3D printing of parts.	Newly founded company. Printing of AM parts	General manager	Worked with AM for three years.
Company 5	OEM	Started their first projects in AM 5-6 years ago	Project manager	5-6 years
Company 6	Certification and verification of parts and production processes.	Developed AM standards since 2015/2016	Senior material engineer and Project lead	Project lead and responsible for standards related to AM
Company 7	End-user	Started AM trials and experiments in 2016. Driver of AM in the Norwegian O&G industry	Leader of the company's AM division.	Worked with AM since 2016

3.3 Data Collection

Data for the thesis was collected using interviews and academic articles. This section will first explain the process related to collecting primary data through interviews and then for collecting second-hand data from academic articles.

3.3.1 Interviews

As briefly mentioned, the sample participants were people in companies Vår Energi ASA know have experience with AM and DI. Vår Energi ASA provided the mail address, where the participants were subsequently asked if they wanted to participate in the master thesis project. The participants received a mail containing three documents containing various information. The first document contained a brief description of the thesis' scope. The second document contained various information regarding practical information, how their data would be stored, and the rights associated with participation. The final document contained a rough outline of the questions they would be asked during the interview. Consent to participation was obtained usually by asking in the mail and again explicitly asking during interviews.

All interviews roughly followed the same format and line of questioning. A generic set of open-ended questions were formulated based on identified gaps in academic literature and questions aimed at answering the research question. However, due to the different types of companies who would participate, questions were adjusted better to suit the participants' presumed knowledge and experience while maintaining the same overall structure. Although a pre-defined set of topics and questions were prepared for each interview, an emphasis was put on maintaining a good dialogue and asking follow-up questions. As more knowledge about the subject was obtained during the interviews, some questions were refined, some were removed, and a few new questions were added. The justification for doing this is that as the interviews progressed, some questions did not seem to gain valuable information. Similarly, as participants repeated certain topics, new questions were added to capture more nuance on a given subject.

All interviews, except one, were conducted using the digital meeting platform Microsoft Teams. Microsoft Teams was chosen due to it being a software participants most likely were familiar with. Online interviews were also chosen due to practical reasons, as participation could be conducted wherever most convenient for the participants, ensuring minimal time usage for participants. Last, Microsoft Teams allow for video recording and real time transcription of the conversation. This feature ensures accurate and efficient transcription of the interview.

The participants were informed that the interview would be last roughly one hour. All interviews were conducted within the suggested timeframe, with the shortest interview being roughly 45 minutes and the longest one hour. Notes and potential follow-up questions were written on a note pad during the interviews. Notes were usually taken if new information was discussed, deserving of further questioning, or requiring further research after the interview. After the interviews, all transcripts created by Teams were cleaned, removing any errors made by the software due to dialects or language differences. When cleaning the data, the video recording of the interviewed was used to ensure that the answers provided by the participants were correctly interpreted and presented in the transcripts. After cleaning, the transcripts were translated into English. Due to practical reasons, one interview was conducted over the phone.

By conducting the interviews digitally, the Microsoft office account issued by the UiS could be used. This is important in the context of data management. Personal information regarding the participants and the information they disclosed during the interviews were stored on the UiS cloud server and not on a personal local hard drive. Section 3.5 Privacy and Ethical Considerations describe how personal data and information were securely stored. A software called NVivo (version 1.7.1) with a UiS student licence was used for coding and categorising interview transcripts.

3.3.2 Academic Literature

The academic literature used in the thesis was found and collected from Google Scholar, ScienceDirect, IEEE, and Scopus. The key words used to search for articles were "Digital inventory", "Digital spare parts", "Additive manufacturing", "Inventory management", "Inventory management strategy", "ERP systems", and "Supply chain management". Logical operators such as "AND", "OR", and "NOT" were deployed in various combinations to widen further the potential for finding articles. Articles were filtered based on relevancy based on the title, and subsequently, the abstract was read. The introduction and conclusion were read if an article was judged as relevant based on the abstract. If a article were considered relevant after reading introduction and conclusion, the article would be read in full and assessed in terms of relevancy and contribution towards answering the research question. A total of 160 academic papers were considered, while only 94 papers meet the inclusion criteria and have been used in the thesis. The articles that met the inclusion criteria were stored using the Zotero citation manager (version 6.0.26).

3.4 Validity and reliability

This section will discuss the various measures taken to ensure the validity and reliability of the thesis' findings.

3.4.1 Validity

Several measures have been taken to maintain the internal and external validity of the research. To ensure internal validity, an interview guide was created as a template for the respondents' questions. As mentioned, minor changes were made according to the type of company a respondent represented. However, great care was taken to ensure that the original intent of the question remained the same. Consequently, although the companies participating in the thesis differ in their role in the AM ecosystem, they have broadly been asked questions about the same topics.

The thesis' external validation has been maintained chiefly in two ways. First, the companies interviewed cover most of the various roles that will use or provide services in relation to the AM digital inventory. While the sample size is small, they collectively ensure that the findings are representative. Second, data from multiple sources sheds light on various aspects of using digital inventories. The information obtained from interviews is compared against findings in relevant academic literature.

3.4.2 Reliability

Reliability has been maintained in a few ways. First, the interview guide has been revised throughout the project to better capture and explore the RQs. Questions that did not yield meaningful answers or participants could not provide useful answers were removed or adjusted. However, the same topics and roughly the same questions have been posed to all participants. Second, all interviews have been conducted under the same conditions, using the same tools for recording and transcription. Third, the data obtained from interviews have been transcribed, cleaned, and coded using a consistent approach every time.

3.5 Privacy and Ethical Considerations

The Norwegian Centre for Research Data (NSD) has externally validated and approved the thesis' plan for handling personal data. The reference number is 108362. Before any participants were contacted, a plan were submitted to NSD detailing the purpose of the thesis, the research methodology, the data sample and how any data would be handled.

The next chapter will discuss the results of interviews and relevant findings from academic literature using the methodology presented in this chapter.

4 Results and Discussion

In this chapter, the main findings from the interviews will be discussed and compared against findings in relevant academic literature. The discussion section is structured as follows: First, an account of the basic concept of DI ecosystems is further explored. Afterwards, the various roles within a DI ecosystem are accounted for using the interviewed participants' descriptions. The findings will be summarised and compared to academic literature findings to answer RQ 1. RQ 2 will be answered following a discussion regarding the challenges companies currently in a DI ecosystem face and the potential implications for using DI. The second section will present a discussion concerning areas which may enable the implementation and utilisation of DIs from an IM perspective. The findings are based on information provided by participants during interviews and expanded upon by relevant academic literature. The discussion of relevant findings will be used to answer RQ 3. Finally, in the third section two decision models related to SP management in the DI ecosystem. The first model will provide holistic overview of the various decisions, stages and involved actors when end users order SPs through a DI ecosystem. The second model is based on the first model but is adapted to inventory reduction situations. The implications of the models will be discussed in light of the RQs and provide strategic advice for DI implementation.

4.1 The AM & DI Ecosystem

Several participants have provided information regarding their interpretation related to various aspects of the value chain related to the AM DI, often called ecosystem by participants. Throughout interviews, respondents have provided answers regarding various roles, responsibilities, what type of companies will exist, and how they will cooperate in the DI ecosystem. First, a summary of the participant's account of the ecosystem will be presented. Second, some of the challenges companies currently in the ecosystem will be discussed. The AM value chain surrounding DI will be called an ecosystem for simplicity's sake.

4.1.1 AM & DI Ecosystem Characteristics

The interviewed companies all seem to agree of the type of companies that will exist in the ecosystem and the services they will provide. The actors in the ecosystem were usually categorised as: End users, service providers, IP owners, independent verifiers, logistics providers, AM part manufacturers, and the digital inventory. A typical description by participants was that all SPs and services would go through the DI, which acts as a hub for the relevant companies. A typical visualisation of the ecosystem structure organisation and various functions is shown in Figure 2. Companies representing all six categories, except logistics, have been interviewed as a part of this thesis. The following section will explain how the interviewed companies themselves envision their role in the ecosystem.

The general idea for the ecosystem, according to Company 1, is to have a centralised digital inventory containing digital files of SPs. The DI is surrounded by companies providing services, AM part manufacturers, end users, companies owning the IP rights to SP files stored in the DI, and others. Companies will request parts and services, send information, and cooperate through the DI. Additionally, the intent is to utilise the distributed capability of storing SP digitally, enabling distributed on-demand production and reduced requirements for physical inventories. Overall, participants seem to have a common understanding of how the flow of goods and information will work in the ecosystem. The descriptions from participants align with Figure 2 in terms of how an ecosystem generally will be structured.

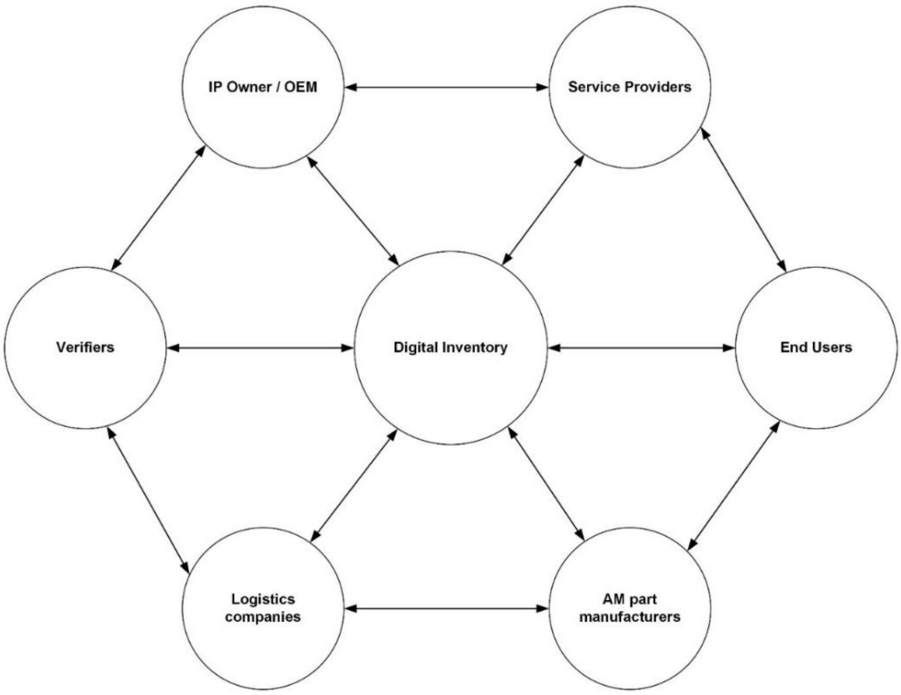

Figure 2. Digital Inventory Ecosystem Structure. From Equinor ASA, n.d., (https://www.equinor.com/energy/3d-printing). Adapted with permission.

Digital Inventory. A common way of illustrating the DI is as the hub of a wheel, connecting the various companies through one central platform (Figure 2). Their main contribution to the ecosystem is twofold: 1) Storage of digital SPs, and 2) provide a platform connecting users of the DI. According to company 1, the main aim of their inventory is to enable on-demand manufacturing of SPs close to the end user's origin of demand. Company 1 noted that its DI could also store digital files for SPs intended for production using CM methods such as CNC. During the interviews, various companies noted some challenges related to using DI, notably the DI operated by Company 1. Primarily, the lack of commercial models was discussed by several participants as a major challenge. Other challenges discussed during interviews were ERP integration, certification and increasing the number of SPs stored in the DI. These issues and the commercial models will be further discussed in section 4.1.2.

End Users. End users represent any company which will request parts and services from DIs. Companies such as Company 7 generally assume the role of an end user in the DI ecosystem. Ideally, they want the DI to contain a large enough selection of SPs that they can realise the potential of on-demand manufacturing and distributed production. Company 7 presented a scenario where an engineer located in Norway can order a SP through the DI, payment is sent to the Italian IP owner, and the SP is printed as needed in Brazil.

From Company 7's perspective, a DI was mentioned as an attractive concept because of a few reasons. First, the potential for significantly simplified SCs. By not having to transport SPs to the same extent as CM SPs, which may only be produced in fixed locations, they foresee a future where SP CAD drawings and print instructions are sent digitally to a manufacturing hub close to the origin of the demand. Second, reduction of supply chain risk. The representative from Company 7 mentioned the blockage of the Suez Canal, the war in Ukraine and Russian sanctions as events imposing significant obstacles to their SC. Local manufacturing of AM SP and simpler supply chains were suggested as factors representing a reduction in SC vulnerability. Third, Company 7 aims to use DI as part of its IM strategies by adding SPs to a DI, thus reducing the need to store physical SPs. Fourth, Company 7 regards DI as potentially being able to reduce its climate footprint. Company 7 suggested that AM and

DI may reduce CO_2 and material waste by cutting the need for transportation, using scarce raw materials, and extending the lifetime of existing equipment.

Company 7 disclosed some challenges related to using the DI. First, the ecosystem represents a significant change to how processes are structured in their SC. Also, as both AM and DI are relatively new concepts, it represents a risk because technical personnel may not fully trust AM compared to SP made with CM methods. Thus, promoting and changing the culture internally represent organisational challenges which must be overcome.

Service Providers. Companies in this category typically provide services relevant to the DI, such as SP scanning, machining, technical assistance, recirculation, and part assembly. Company 2 would typically fall under the service provider category as the company specialises in digitalisation. According to Company 2, they will provide services to the DI by scanning physical SPs and creating 3D models. The SPs are subsequently turned into CAD models and added to a DI, which is available for end users. Company 2 envision that they could contribute in reducing physical inventories by scanning parts and uploading the digital part file to the DI. Company 7 has ambitions of forming local hubs with service providers close to their production centres at various locations. An example was given where companies, such as recycling or machining services, are close to where the SPs are printed and distribution centres.

IP Owners & OEMs. An IP owner is typically considered a company which owns the IP for a given SP stored in a DI. Most interviewed companies have a common understanding that OEMs will generally be the type of company owning SP IP. Also, the OEM will hold a central role in supplying the DI with SP models. Company 1 envisions that OEM will also contribute with design and engineering expertise. Company 5 do not foresee that they will print AM parts themselves. Instead, OEMs role will entail being problem solvers providing technical assistance, for example in certification processes. Another reason the company will not engage in AM printing is due to the rapid development of AM technology.

The move towards a DI represents a significant change in the business model for IP OEMs. Companies 1, 2 and 7 discussed how DI would change how OEMs supply SPs. According to

Company 1, OEMs gain revenue from selling physical SPs in volume. The DI represents a scenario where end users only purchase needed SPs, which significantly changes how OEMs conduct their business. Company 5 said that testing the commercial conditions is the main focus area of the DI pilots they are currently involved in. Another critical concern mentioned by Company 5 relates to qualification. The Company 5 representative wanted to add certified SP to the DI. However, the current process of obtaining certification was characterised as expensive and time-consuming, a notion shared by both Company 1 and 7. Commercial and qualification related challenges to the DI will be further discussed in section 4.1.2.

Independent Verifiers. Companies providing independent verification will play a crucial part in the ecosystem. The representative from Company 6 stated that their company would "*develop and deliver auditing and approval of manufacturers and create the certificate scheme for manufacturers and processes and parts*" concerning AM and DI. The company has developed some AM standards and certification schemes already adopted by some companies. Certification of parts, processes and companies is essential to several of the companies interviewed. Companies 1, 2, 4, 5, 6 and 7 discussed the topics related to certification to some degree. Based on the companies' accounts, independent verifiers will be important in verifying that companies, processes and SPs comply with standards such as NORSOK.

On-Demand Manufacturing. Companies belonging to this function are typically companies with AM printing capabilities. Companies 3 and 4 belong to this group. Company 3 has already printed several polymer parts for end users in the Norwegian O&G industry. Most of the company's orders come from industries other than O&G, such as defence and military. Company 3 is familiar with a DI, but most AM parts are ordered outside of any DI. It was suggested during the interview that while printing is a core part of their activities, much time is also spent providing AM technical advice to customers. Based on the information obtained in interviews, Company 4 has ambitions of becoming another AM part manufacturer in an O&G hub in northern Norway.

Logistics. Logistical companies are responsible for transporting printed SP to the origin of demand. According to Company 7, a key ambition is a collaboration with logistics companies capable of providing SP on-demand. In this regard, the representative said it has looked into using drones to deliver SP off-shore on-demand. The company representative also said they would prefer using drones rather than the more traditional transport method of supply vessels due to the on-demand capabilities associated with drones.

Comparing the DI Ecosystem Against Academic Research. The ecosystem commonly envisioned by the participants broadly aligns with how similar ecosystems have been described in academic literature. This section will compare the characteristics of the DI ecosystem described by interview participants against three different proposals suggested by Chekurov et al., (2018), González-Varona et al., (2020) and Salmi et al., (2018) respectively.

Chekurov et al., (2018) conducted a study aiming to assess the benefits of AM in an SP supply chain using focus group interviews, including participants representing various functions in a DI ecosystem. The participants in the study broadly align in terms of the type of companies and roles necessary in a DI ecosystem, the use of one central digital platform for SPs and a preference for AM manufacturers located close to demand. However, the study's participants would prefer a DI model where OEMs jointly own the DI. In contrast, Company 1 is an independent software company hosting a platform for digital SPs. Figure 3 (Chekurov et al., 2018) shows how the study's participants preferred structuring a DI network (ecosystem).

Figure 3 summarises how OEMs in the Chekurov et al., (2018) study believe a DI ecosystem would best be structured. First, the end user requests a part. The request is relayed to the OEMs who operate the DI. Information regarding demand material is sent to material suppliers. The CAD model is sent to an independent AM service centre where the CAD model and manufacturing instructions are formulated. The CAD model, manufacturing instructions and AM print material are sent to the manufacturer of the AM SP. Finally, the part is transported to the end user.

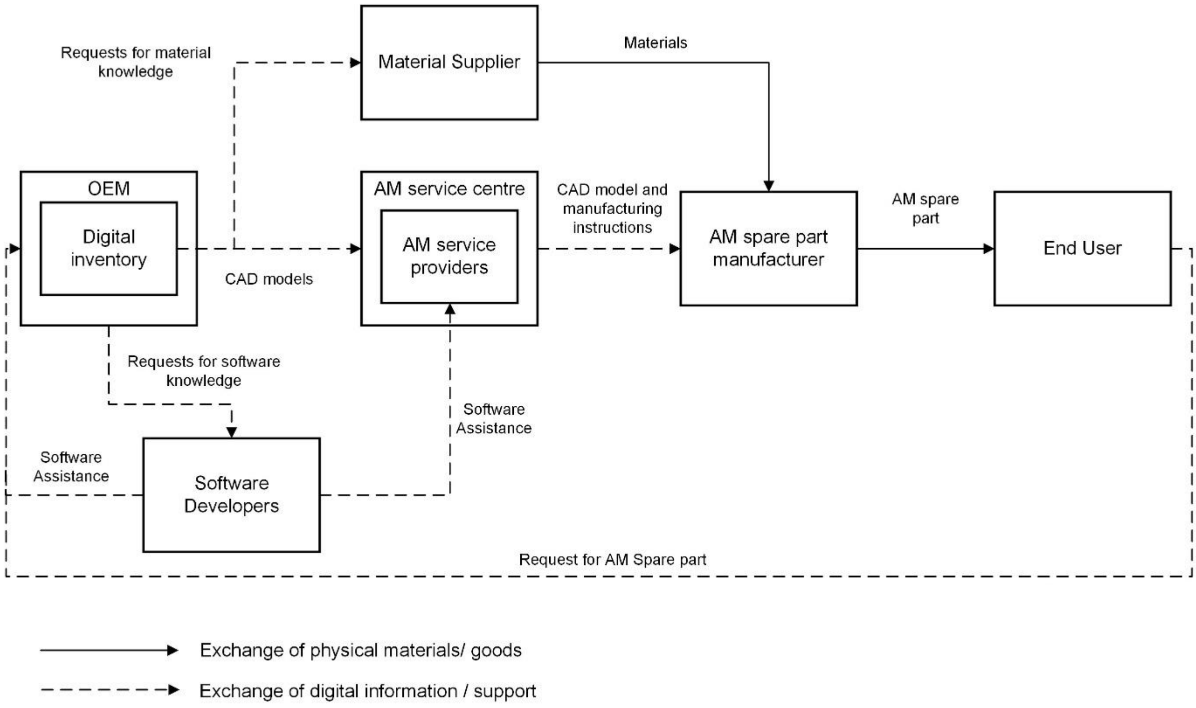

Figure 3. OEM-centred digital SP network. Adapted from "The perceived value of additively manufactured digital SPs in industry: An empirical investigation" by S. Chekurov et al,. (2018), *International Journal of Production Economics*, *205*, p. 93. Retrieved from https://doi.org/10.1016/j.ijpe.2018.09.008, Adapted with permission.

González-Varona et al., (2020) assessed the benefit of distributed production of AM SP using DI. The study also presented a generic model of an ecosystem, including the various roles and flow of information, payment, and data. The model presented by González-Varona et al., (2020) (Figure 4) differs slightly from the participants' preference in the Chekurov et al. (2018) study. The main difference is that the DI were not commercially available and financed by the European Commission. The companies involved in the case study were small-medium enterprises (SMEs). However, González-Varona et al. claim that the model could be applied to larger industries (2020). This seems like a reasonable claim as their description of how the DI will function align well with how interview participants describe their ideal organisation of a DI ecosystem. Notably, the model presented by González-Varona et al., (2020) also emphasised the fact that companies can choose which companies they want to perform various jobs related to an ordered part, such as verification, if necessary, printing, and transportation.

In the model presented by González-Varona et al., (2020), the digital inventory is a separate entity in the ecosystem where companies have separate roles in the DI ecosystem. Once a SP is requested, payment is also sent to the DI. A royalty fee is directly sent to the OEM or the IP owner if the CAD model is already stored in the DI. If the CAD model is not stored in the DI, the OEM uploads the CAD file to the CAD model catalogue. The AM SP manufacturer receives payment and the information required for manufacturing. After manufacturing, the part is picked up by a logistics provider and sent to the end user.

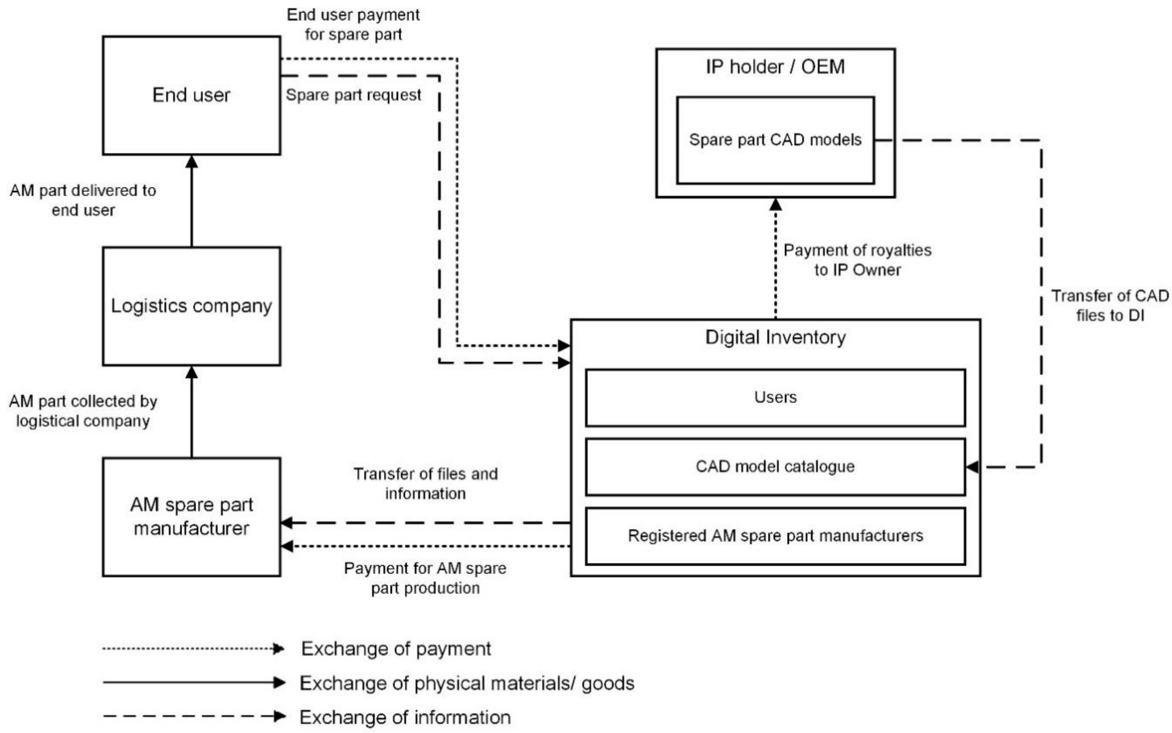

Figure 4. Independent Digital Inventory Ecosystem Flow Diagram. Adopted from "New business models for sustainable SPs logistics: A case study" by J. M. González-Varona, 2020, *Sustainability*, *12(8)*, p. 4, https://doi.org/10.3390/su12083071, CC-BY.

In a report aiming to assess the business concept and various other aspects of using AM and a DI ecosystem in a SP context, Salmi et al., (2018) proposed five different models for organising an DI ecosystem. These models were placed on a scale depending on the degree of centralisation. Of the five proposed models, the "*3D database operator-centric model*" (Figure 5) was considered the most similar to the ecosystem described by the interviewed participants. The 3D database operator-centric model is operated by an independent company solely responsible for the digital SP inventory. Also, OEMs are responsible for adding digital SPs to the inventory. Thus, the model aligns with the DI ecosystem proposed by interviewed companies. A key difference in the model proposed by Salmi et al., (2018) is that end users are responsible for quality assurance. In the ecosystem described by interview participants, quality assurance, such as qualification and verification, will be conducted by companies specialising in verification and qualification.

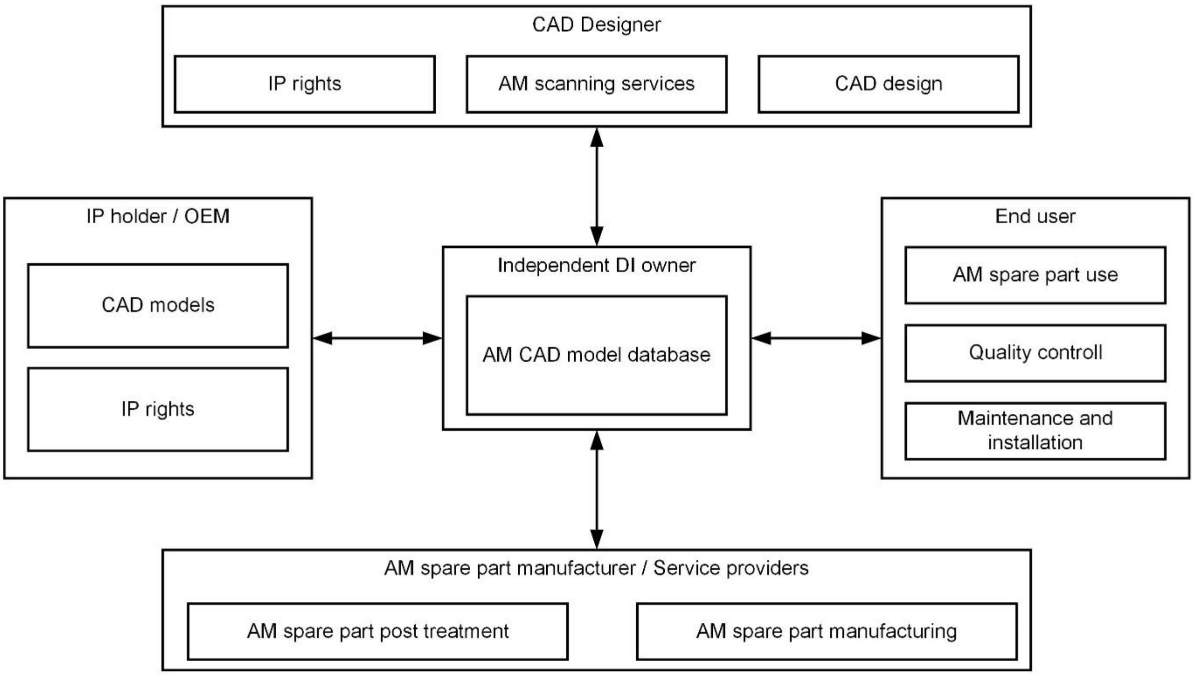

Figure 5. The 3D database operator-centric model. The illustration shows how actors in a DI ecosystem are organised around the DI. Adapted from “Digital SPs”. 2018. (http://urn.fi/URN:ISBN:978-952-60-3746-2). Adapted with permission.

Summary of DI ecosystem characteristics. The very concept of a DI ecosystem for AM SPs is relatively new. As such, academic literature concerning the concepts of AM, DI and digital spare could be said to suffer from low maturity. Currently, few real-world examples currently document the implementation of DI ecosystems on an industrial scale (Cardeal et al., 2022).

Salmi et al., (2018) proposed five different models and placed them on a scale from "centralised" to "Decentralised". Figure 5 was the most structurally similar to the description of an existing DI ecosystem described by interview participants. Further, according to Salmi et al., (2018), Figure 5 represents the middle point on the scale of "centralised" to "Decentralised". Suggesting OEMs and end users maintain close to equal influence in the ecosystem. Evidence backing the notion of equal influence by OEMs and end users in Figure 2 can be found through interview statements. Several companies emphasised the importance of collaboration between actors in the ecosystem. Company 5 suggested that collaboration will lead to lower delivery times and more qualified SPs added to the DI.

In contrast, Chekurov et al., (2018) presented a model based on how OEMs believe a DI ecosystem should be structured. The OEM companies in the study favoured a DI model where they still stored digital SP files on their servers. Reasoning that OEMs are concerned with storing files securely. Thus, OEMs indicated a preference for a centralised model where OEMs are more in control of the storage and usage of their files. A few interviewed companies directly addressed concerns regarding securing and protecting digitally stored files in the DI of Company 1. For example, Company 6 mentioned how OEMs could limit the detail and information available for a given file in the DI. Also, files can be encrypted as they are sent to a manufacturer. However, the Company 6 representative also emphasised the importance of cooperation and trust between companies in the ecosystem.

The model proposed by (González-Varona et al., 2020) is the model most similar to the description provided by the participants. In both models, the DI is independently operated, with external companies linked to the DI providing digital files, services, and AM SP manufacturing. In the case presented by the study, a hospital in Argentina could obtain an AM SP quicker and cheaper than they would have been using traditional manufacturing. The SP used in the study was stored in a DI, and the IP of the part belonged to a Spanish manufacturing company. Due to the model, time was saved by omitting production in Spain, transport internally in Spain, transport by plane from Spain to Argentina, customs processing in Argentina, and transportation from customs to the hospital in Argentina. By utilising the a DI AM CAD models were instantly sent to a manufacturer locally in Argentina and the printed SP was distributed from the manufacturer to the hospital. The effective time saved by using an DI was 23 days.

In summary, the model presented by González-Varona et al., (2020) seems to have characteristics well suited to enabling the proposed benefits of DI and the surrounding ecosystem from an IM perspective. The reduced lead time and requirement for physical storage due to SP being printed virtually on-demand thus facilitate a conclusion that the model contributes towards a pull-based IM strategy. As such, the answer to RQ 1 is that the DI ecosystem proposed by participants (Figure 2) is aligned with ambitions and capable of potentially enabling the realisation of the proposed IM benefits of DI. The conclusion to RQ 1 is conditional on the challenges discussed in section 4.1.1 being appropriately addressed.

4.1.2 Current Challenges in the Ecosystem

A few topics were repeatedly discussed throughout the interviews as barriers to increased AM and DI development. The reoccurring topics have been separated into 1) Issues in current procurement processes, 2) Commercial uncertainty and 3) Other challenges. These barriers will be discussed and compared to findings in academic literature. Finally, the barriers and potential implications of implementing a DI as a part of a larger IM strategy will also be discussed.

Procurement Challenges. During the interviews with Company 3, some problematic aspects related to how certain O&G operators conduct their procurement processes and payment were discussed. Company 3 expressed some frustration with certain O&G operators' procedures when ordering AM SPs. This section will present some of these challenges.

In general, Company 3 has found some O&G operators' procurement processes to be challenging to work with. More specifically, the processes leading up to an order, how orders are made, invoicing and payment were mentioned as particularly challenging aspects. The Company 3 representative, in general, experience that people from O&G operators have little technical knowledge about the production process associated with AM. For example, the lack of knowledge reveals itself in AM orders with deadlines not technically feasible. When people from O&G operators have placed orders in the past, the lack of knowledge contributes to being unaware of the actual limitations AM. Also, the lack of knowledge often leads to much back and forth before a usable SP is printed. Not only does this ensure a longer production process, but Company 3 has also often experienced that the final order, after much back and forth, is not an order that will be profitable to manufacture. Company 3 often experiences that when

O&G operators engage the company, they are often told that a given SP is needed urgently. Subsequently, production capacity is made available by suspending other print jobs and prioritising the O&G operators' order. However, when Company 3 have reached out to the people who made the order for general follow-up or technical assistance, they are slow to respond or do not follow up on the order themselves.

The final challenge expressed by some of the interviewed companies relates to invoicing and payment. Company 3 has received orders from O&G operators before a purchase order (PO) has been created. When the part has been printed, and the invoice is sent to the customer, the invoice is rejected by the O&G operator because the invoice has not been marked with a PO number. In several instances when Company 3 has requested a PO before creating an invoice, the customer is slow to respond. Another example was provided when company 3 printed a urgently needed SP for an O&G operator. For context, the O&G operator would potentially have to commence a shutdown of the asset if a replacement SP was not obtained immediately. Company 3 provided the printed SP, the SP was received by the O&G operator, installed offshore and a shutdown was avoided. However, Company 3 did not receive payment according to the invoice due date. When Company 3 inquired about payment for the part, the company was told payment could not be conducted because the goods receipt had not been sufficiently conducted when the O&G operator received the SP from Company 3. The representative for Company 3 noted that compared to companies in other industries, O&G operators are significantly worse at paying invoices on time. Further, in general, the company find that the largest customers are the worst in terms of payment.

Concerning RQ 2 and 3, the issues Company 3 face represent barriers towards achieving implementation of a DI as a part of a larger IM strategy in a few ways. The issues mentioned above faced by Company 3 signify that the transition towards using AM SP requires procurement processes capable of capturing the suggested advantages of DI. The importance of ensuring streamlined procurement and supply chain processes may increase with implementation of DIs. Company 2 suggested that storing SPs in a DI instead of a physical inventory will increase the pressure importance of actually receiving ordered SPs when they are needed as they cannot be picked from inventory anymore. Company 6 offered an analogy that when companies remove SPs from their inventory and transition towards an on-demand manufacturing strategy, they essentially replace the physical part with trust that a given SP can be printed according to their needs. As such, DIs represent a supply chain risk as SPs previously available on hand are no longer readily available in a physical inventory. End users must ensure that internal supply chain and procurement processes maintain control of all stages of an AM SP order made through a DI.

Commercial Uncertainty. As mentioned earlier, developing commercial models for the DI is currently one of the primary concerns and topics of discussion in relation to DI ecosystems. Company 5 disclosed that the commercial aspects of AM and DI are their primary focus in AM pilots. Company 1 also told during interviews that they are engaged in a joint industry project (JIP) where assessing different commercial models is a primary objective. Based on an overall impression from the interviews, OEMs play an essential part in the ecosystem as their prominent role entails supplying the DI with digital parts. Several of the interviewed companies recognise the change a DI represent to an OEMs business model and, therefore, why some OEMs are hesitant in embracing DIs.

According to Company 1, OEMs have traditionally operated with a business model where they are paid to sell physical products. A DI represents a business model for OEMs where customers only pay for the needed SPs on demand. DI will mean a shift from selling physical products to digital products. Knofius et al., (2016) also suggested that OEMs hold a favourable position when sourcing options are limited, and parts are obsolete. For the latter, it was suggested that when an OEM no longer offers a SP, the end user is often forced to purchase more parts while the part is still available. As such, the transition towards increased use of AM and a DI represents a significant change to OEM's business model and strategic position. (Cardeal et al., 2022; Knofius et al., 2016).

The topic of developing commercial models for OEMs concerning AM and DI has received little attention in academic literature. (Yue Zhang, Westerweel, Basten, & Song, 2022) suggested drawing inspiration from the telecommunication industry, proposing a fixed licencing fee and per unit royalty fees. Their study assessed various IP licensing structures, IP licence influence on OEM profitability and how to structure IP licences to enable the benefits of DI. Their study generally found that OEMs utilising IP licencing can expect the model to be profitable. The proposed payment model by Zhang et al., (2022) supported DI potential towards distributed, on-demand manufacturing. In the case presented by González-Varona et al. (2020), the IP owner of a part added to the DI also received payment based on licencing and royalties per part. The price for a given part was the sum of IP owners' royalties and the AM manufacturer's price for printing the part. The DI charges a percentage from the price of the IP owners' royalty and AM manufacturers. This payment structure was used to reduce the price for end-users.

The lack of academic attention significantly contrasts the considerable attention commercial models are given by some of the interviewed companies. In this regard, the attention is related to developing commercial models ensuring that DI is an attractive business proposition for all companies in the DI ecosystem. However, it should be noted that OEMs were most frequently mentioned in relation to the lack of commercial models. Company 7 said, "*We have no commercial or contract models to cover it*", related to issues with using DI which are yet to be resolved. As stated by companies 2 and 7, the benefits of using a DI cannot be realised without thousands of parts stored in the inventory. As the intention is, among other things, for OEMs to populate the DI, developing attractive commercial models for OEMs is also essential from an SCM and IM perspective.

While the commercial models for OEMs might not address how to implement a DI directly, OEM participation may indirectly influence how DI is implemented as a part of an IM strategy. First, OEMs usually stop offering parts when the economic conditions favour newer parts, either because of reduced demand or because related equipment is nearing the end of life (Yue Zhang et al., 2022). Thus, end users are forced to buy safety stock for when the part is discontinued (Cardeal et al., 2021). By providing attractive commercial models for OEMs in the DI ecosystem, SPs can be added to the DI and still be printed on-demand when a given SP no longer is profitable, or the OEM has discontinued manufacturing (Song & Zhang, 2020). In the described scenario, SP are still available through the DI and can be easily adjusted according to end-user needs. Also, AM and DI can enable OEMs to gain revenue on SP which before would have been regarded as no longer profitable. In relation to RQ 3, an increased number of OEMs providing SP to a DI would provide end users increased sourcing alternatives for SP and reduce reliance on a small number of OEMs (Cardeal et al., 2021; Knofius et al., 2016).

Other challenges. Participants also mentioned two other challenges repeatedly. The first is related to the qualification of AM parts and processes. The second challenge repeated by all companies, except Company 7, was the lack of demand for AM parts from end users.

The topic of qualification was often mentioned as a significant challenge in relation to AM and DI. Qualification in this context refers to verifying that AM production processes and the subsequent AM parts follow specifications and quality standards according to Company 5. Another vital aspect of qualification mentioned by Company 4 is that qualification of processes and parts enable traceability and documentation.

Companies 1, 5 and 7 highlighted that current qualification processes are expensive and time-consuming. Company 1 said they had experienced projects becoming unfeasible due to the increased costs and time delays due to the qualification process. Others mentioned that knowledge related to establishing AM procedures in line with relevant standards is hard to come by, especially for smaller companies. Company 6 noted that the qualification requires a high degree of knowledge related to production, quality, procedures and quality systems documentation. Another factor contributing to the qualification being a barrier is uncertainty regarding applying existing standards with standards created for AM processes and parts.

Although several companies mentioned qualification as a challenge, potential solutions and mitigating factors were also discussed. For example, Company 1 mentioned the potential for digital qualification processes. While the representative said this solution is not currently feasible, digital qualification of SPs was suggested to enable a more cost- and time efficient qualification process. Company 5 mentioned close collaboration with O&G operators as a significant factor contributing to more efficient qualification processes.

Most of the companies in the DI ecosystem mentioned the lack of demand for AM parts by end users, such as O&G operators, as a barrier to increasing the usage of AM and DI. According to Company 2, the O&G operators' approach to using AM SP could be considered as ad-hoc. Instead, the representative suggests that O&G operators should show more commitment to AM and DI if O&G operators want to reduce their physical inventories, costs, and SC risk. This sentiment is shared by Company 3, who also believes a more comprehensive and committed approach from O&G operators would benefit everyone in the DI ecosystem. The lack of demand was also suggested as an obstacle to investment in new materials, machines, and people for companies like service providers, OEMs and AM part manufacturers. Company 3 disclosed that with the current demand for AM by end users in the O&G industry, the company would not invest in additional machinery due to the high investment cost and uncertainty of whether demand would support the investment costs. Relatedly, Company 2 said that SP with complex internal structures requires scanning by expensive CT machines. With the current demand, the company cannot justify investing in that type of machinery. In terms of enabling the use of DI as a part of an IM strategy, the main barrier related to lack of demand was suggested by several companies as the low rate of SP being added to DIs.

However, the Company 7 representative answered the calls for increased demand from end users by stating that the company currently has several large ongoing projects deserving of attention. Further, AM projects must go through the same internal decision processes as any other project. Therefore, the representative stated that the company is not in a position to make any specific commitments related to how much the company will spend on AM in the future. The representative said the company has clear ambitions of using AM and DI to enable significant physical inventory reductions, increased purchasing of on-demand parts, and transferring items from physical inventories to DI. Company 7 believes that actors in the DI ecosystem should become sustainable companies without large commitments from end users such as O&G operators. As such, Companies in the DI ecosystem should obtain orders and experience from other places while the demand from O&G will gradually increase.

While lack of demand was mentioned as a significant barrier, it has been considered out of scope for the thesis. However, the topic of qualification will be further considered in section 4.3 SP Decision Model. The following section will discuss potential enablers for implementing

AM and DI in an existing IM strategy based on key findings from interviews and academic literature.

4.2 AM & DI Ecosystem Supply Chain Implications

This section will further discuss potential implementation enablers of DI to O&G operators IM strategies and aim to answer RQ 3. During interviews, two aspects were mentioned as highly important for implementing DI as a part of an IM strategy. These two aspects will be discussed in light of RQ 3 in the following order: 1) Integration between DI and ERP systems, and 2) Frameworks for determining AM SP suitability.

4.2.1 DI Integration with ERP and Procurement Software

This section will discuss DI integration with ERP and procurement software commonly used by Norwegian O&G operators. The section will also discuss some of the main challenges and benefits of ERP integration. Advice based on findings from interviews regarding actual implementation is also presented.

Company 1 provides two options for accessing the SP stored in the DI. Companies can access the DI through the DI application interface or application programming interfaces (API) connecting the DI with typically ERP or procurement software. Company 1 disclosed that they have already created some APIs for integration with the ERP system used by all O&G operators. However, although many O&G operators utilise the same ERP software, they use different versions. Therefore, the continuing development of APIs allowing for easy integration is a key focus area for Company 1.

Company 7 is one of the companies that already has integrated a DI into its procurement system. According to Company 7, this procurement system is an e-catalogue containing parts and material numbers. In turn, this procurement system is connected to Company 7’s ERP system (Figure 6). When asked why the DI was not directly integrated into their ERP system, the representative said that the ERP system they use is hard to integrate into. Therefore, the DI was integrated with the procurement e-catalogue, which is already integrated with the ERP system. According to Company 7, ensuring a one-to-one match for all SP material numbers were a key area of fucus during the integration process. In this regard, data migration reliability have been identified as essential to ensure the successful integration of two data systems (Matthes, Schulz, & Haller, 2011). The company also recommended this integration approach for other companies instead of integration directly into the ERP system.

Another aim throughout the integration process for Company 7 was to ensure AM SPs from the DI were easily accessible. Also, procuring SP from the DI should be equal, or ideally easier, than procuring any other SP. Company 1 further stated that ease of use is something they focus on to a large extent when developing APIs. This approach aligns with the findings of Mahmood et al., (2019), which identified in an extensive literature review that change management and systems integration are the most common challenges companies face concerning ERP projects. Change management was highly ranked due to people's tendency to resist change and because they want to maintain their work habits. As for systems integration, the Mahmood et al., (2019) article found that integration of new modules with ERP systems, poor integration strategies and lack of alignment with existing processes often resulted in poor execution and low acceptance among intended users. Both Company 1 and 7 emphasised how they aim to avoid some of the commonly experienced ERP integration issues by focusing on easy access and ease of use. Thus, according to Company 1, companies wanting to integrate DI into their ERP systems should aim to: 1) Ensure that integration does not make existing processes harder. Ideally, processes should be simplified post-integration and, 2) Integrate DI so AM SP are easily accessible through relevant software.

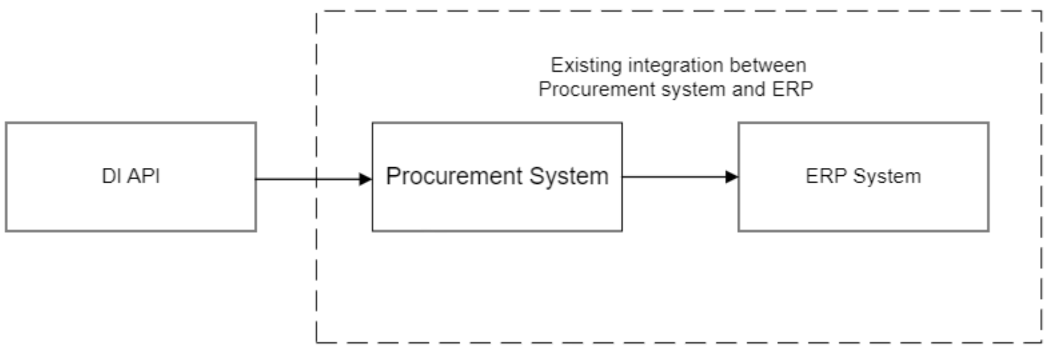

Figure 6. Company 7’s approach for integration between DI and its procurement system.

Another factor highlighting the importance of integration with ERP systems is that ERP systems are not only used for SCM and IM. Larger ERP software also typically carries functionality for finance management, human resources (HR), project management and many other functionalities (Samaranayake, 2009). Ensuring that as many stages of the process involved in ordering SP can be linked to existing ERP systems will be necessary (Do, 2017). The Company 1 representative also mentioned that they are developing methods for handling contractual matters aiming to streamline and automate this aspect of the procurement process. He continued to explain that finding automated solutions where parties do not have to physically sign a piece of paper while still ensuring that all parties mutually understand the terms agreed in the contract was essential to ensure the commercial side of the DI would work.

In relation to RQ 3, there are several potential benefits associated with integrating DI with existing ERP and procurement software. According to Company 7, DI integration with existing systems would allow easier access to information from the DI. From Company 7s perspective, this is useful as they have other digitalisation projects ongoing where access to SP information would be useful. Also, integration with existing procurement and ERP software limits the requirement for users to gain familiarity with new software. Ensuring ease of use and easily accessible AM SP were repeatedly mentioned as a critical consideration for Company 1 in developing APIs for their DI. Further, ERP integration would also limit the requirement for developing new or adjusting procurement processes, enabling the use of DI, according to Company 1. As such, integration with ERP can be seen as an enabler for DI implementation.

4.2.2 AM SP Suitability

This section will discuss how an O&G operator may evaluate which SP in their inventory possess characteristics suitable for AM. The topic has implications for IM as both Vår Energi ASA and Company 7 stated they have ambitions of using AM and DI to reduce their physical inventories considerably.

Company 7 stated during interviews that they have a short-term vision of reducing their inventory by 25% and long-term by 50%. At the same time, they want to add SPs to DIs. The participant said that the company currently possesses an inventory valued at 27 billion NOK and estimates that 80% will not be used at any time. Further, virtually all companies interviewed stated that a key benefit associated with AM and DI was the potential for reducing the number of physical SPs in inventories and instead storing parts digitally. However, little information was provided in terms of actionable advice regarding how O&G operators should proceed. The participant from Company 2 was the only respondent briefly mentioning data in relation to physical inventories. When asked about their experience in reducing inventories, he disclosed that they are in discussions with some O&G operators but have yet to reduce any large inventories. Further, he stated that:

> They have ok data to work with. I have worked with inventory planning before in other industries. Then we had even more data, so it was easier to look at how often you used a part, how old it is and what it is made of and more.

From an inventory reduction perspective, data regarding inventory item characteristics are important for identifying SPs suitable for AM and, subsequently, for inclusion in a DI (Kostidi, Nikitakos, & Progoulakis, 2021). Data related to SP characteristics and how a given SP will be used are the most critical aspects in determining digitisation suitability (Chekurov et al., 2021). The most commonly mentioned SP characteristics determining AM suitability (Table 4) are small part size (Baumers & Holweg, 2019; Kunovjanek, Knofius, & Reiner, 2022), small order batches (Westerweel et al., 2018), infrequent demand (Kostidi et al., 2021), high part value (Kunovjanek et al., 2022), high design complexity (Togwe et al., 2019) and high supply chain risk (Knofius et al., 2016). Also, because SP used in the O&G industry are considered capital goods and have long lead times, the use of AM presents a significant SCM opportunity (Mecheter et al., 2022).

Table 4

Characteristics determining SP suitability for AM.

Characteristic	Description	Source
Small part size	Current AM printers have limited build chambers and production unit costs compared to CM.	(Baumers & Holweg, 2019; Kunovjanek et al., 2022)
Small order batches	Small order batches facilitate lower lead time.	(Westerweel et al., 2018)
High value	AM is most suitable for creating SPs of high value.	(Kunovjanek et al., 2022)
High design complexity	AM enable production of parts not possible to create with CM methods.	(Togwe et al., 2019)
High supply chain risk	AM could be used as an additional SP sourcing option, increasing SC flexibility.	(Knofius et al., 2016)

Lindemann et al., (2015) presented a bottom-up approach utilising workshops for identifying potential AM candidates (Figure 7). The framework consists of three stages: the AM information-, SP assessment-, and AM SP decision stage. The Lindemann et al., (2015) framework aims to enable SP suitable for AM by inexperienced and experienced with AM in a time and resource-efficient process. In the assessment stage, workshop participants receive information regarding the benefits and limitations of AM. A rough estimate of potential AM SP is selected from the relevant inventory. The assessment stage involves further filtering of SP candidates using a set of criteria relevant to the industry and the company. In the final decision stage, increased emphasis is placed on obtaining required information related to the remaining SP candidates' requirements. Subsequently, the SP presenting the biggest overall fit for AM production and benefit to the company are identified.

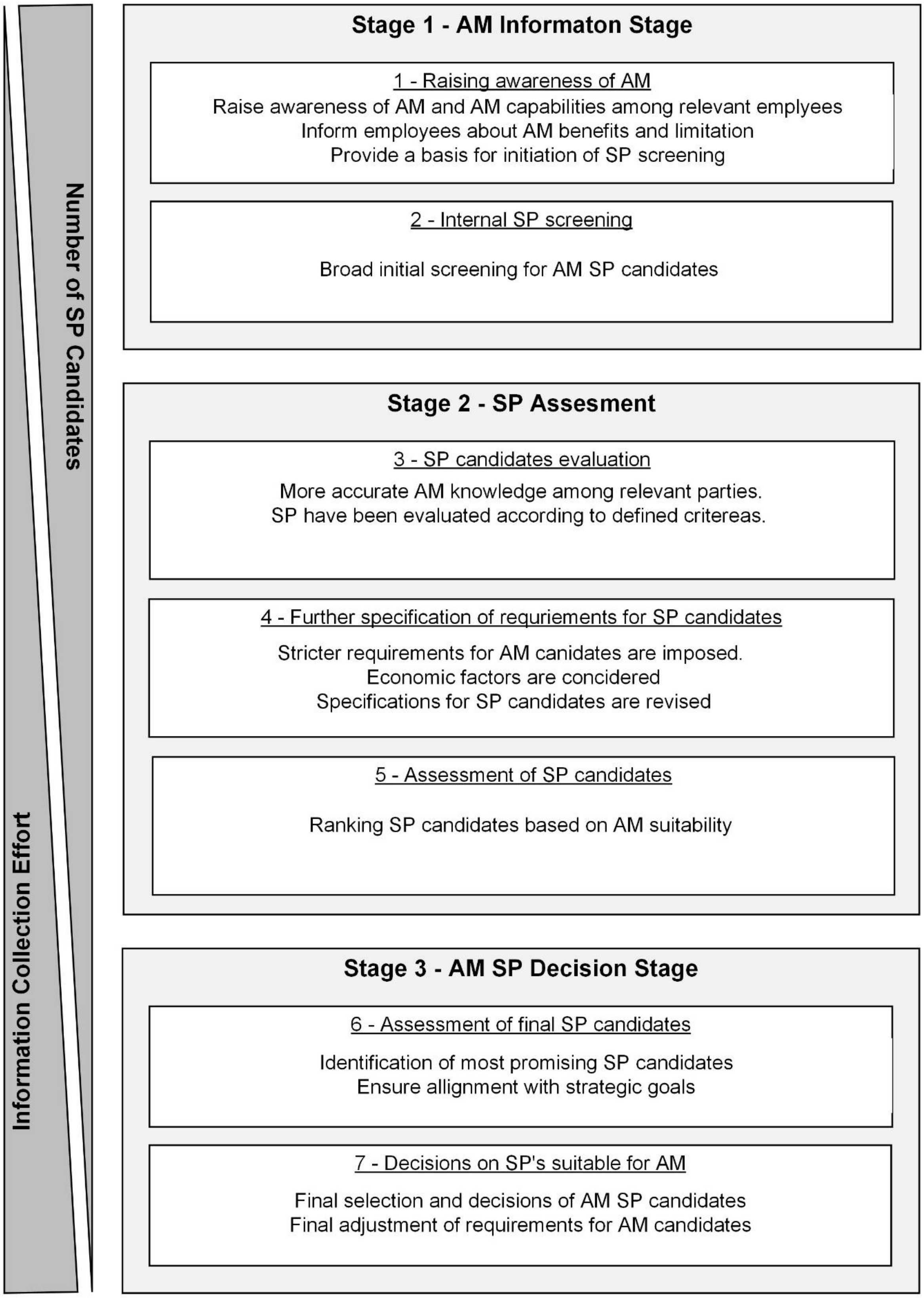

Figure 7. Bottom-Up Workshop Approach for Identifying AM Candidates. Adapted from "Towards a sustainable and economic selection of part candidates for additive manufacturing" by Lindemann, C. et al., 2015, *Rapid Prototyping Journal*, *21(2)*, p. 218, https://doi.org/10.1108/rpj-12-2014-0179. CN BY-NC.

In contrast, Knofius et al., (2016) argue that the framework presented by Lindemann et al., (2015) may not enable the involved people to assess large enough inventories. As such, the authors argue that potential candidates may be overlooked. Instead, Knofius et al., (2016) propose a top-down approach, utilising inventory data and ranking attributes according to company goals to determine AM candidates. Both technical- and inventory-related data could be obtained from company ERP software (Metsä-Kortelainen, Reijonen, Riipinen, & Vaajoki, 2020). However, Metsä-Kortelainen et al., (2020) warn that the process of identifying suitable SPs is highly challenging, especially when inventories consist of several thousand items and material records incomplete. Therefore, companies should pay attention to obtaining as much data regarding their SPs and storing it systematically (Salmi et al., 2018).

The current academic literature has yet to produce many frameworks for how companies should approach inventory reduction using AM and DI. However, the frameworks presented by (Lindemann et al., 2015) and (Knofius et al., 2016) have been tested in real-world cases and have been proven to identify thousands of SPs suitable for AM in companies with large inventories (Khajavi et al., 2020). Knofius et al., (2016) suggested combining their top-down framework with the bottom-up framework presented by (Lindemann et al., 2015), arguing that combining the approaches would allow for an analysis of more parts while involving relevant company personnel in the identification process. As such, identification of SP with characteristics suitable for AM address RQ 3 by potentially identifying SP that currently are stored physically but could be added to a DI instead. Thereby both reducing items in stock and increasing the number of available SP in a given DI.

4.3 SP Decision Model

Based on the findings and discussion in Chapter 4.1 and 4.2, a decision model for SP in the context of AM and the DI ecosystem has been developed (Figure 8). The decision model aims to visualise the various stages a SP may go through in a DI ecosystem. The various decision gates and stages are based on information from interviewed participants and academic literature. The decision model covers aspects such as AM SP suitability, availability, certification, and the need for technical assistance.

The model is initiated with a demand for a given SP with an end user. The end user investigates whether the SP is already available in the physical inventory. A decision is made on whether the SP has characteristics suitable for AM, regardless of whether the SP is stored in the inventory. The end user utilise frameworks for determining AM suitability like those presented by Lindemann et al., (2015) and Knofius et al., (2016). Either way, if the SP is not suitable for AM, the SP is ordered as a CM SC. As such, assessing which items in the inventory possess characteristics suitable for AM is a crucial enabler for an expedient process.

If a SP has been determined not available in the DI, but the SPs has favourable AM characteristics, the end user may check if the needed SP is available in the DI. A decision regarding whether the SP need to be qualified should be taken early in the process as qualification significantly impacts the process of ordering AM parts through the DI. Company 5 mentioned that the certification process for AM parts increases lead time and costs. The Company 5 representative estimated that 70% of the time consumption of preparing a SPs for AM is related to certification and represents 30% of the associated cost. However, once the production process, the SP, and the machine which produces the SP are qualified, the next SPs will use less time. Due to the consequential impact of the certification process, the decision of whether a SP needs to be certified should be taken as early as possible. If the SP does not need certification, relevant companies may utilise the ecosystem to request technical assistance from other actors in the ecosystem.

If the SPs is stored in the inventory and has characteristics suitable for AM, the end user could contact companies in the DI ecosystem providing 3D scanning services. The 3D scanning company would assess whether the demanded SP is covered by IP protection. If a SP has IP protection, company 2 suggested the best option was to contact the IP owner and collaborate on adding the SPs to the DI. Should IP protection not cover the SPs, the service provider scans and uploads the SPs to the DI. The model then repeats from the decision gate where one considers if the SP need to be qualified.

Once a SP is qualified or ready for production, the CAD model is uploaded to the DI accompanied by manufacturing instructions. An AM SPs manufacturer receives a file containing only the specifications needed to print the SPs. Based on the order, the AM SPs manufacturer estimates material requirements and determines if an order for AM material is needed. If the AM SPs manufacturer needs additional AM material, an order for material is sent to a service provider specializing in AM print materials. When the material is ready, it is collected by a logistics company and delivered to the AM SPs manufacturer. Suppose there is no need for additional AM material orders. In that case, the SPs is printed, picked up by the logistics company and ultimately delivered to a specified location by the end user.

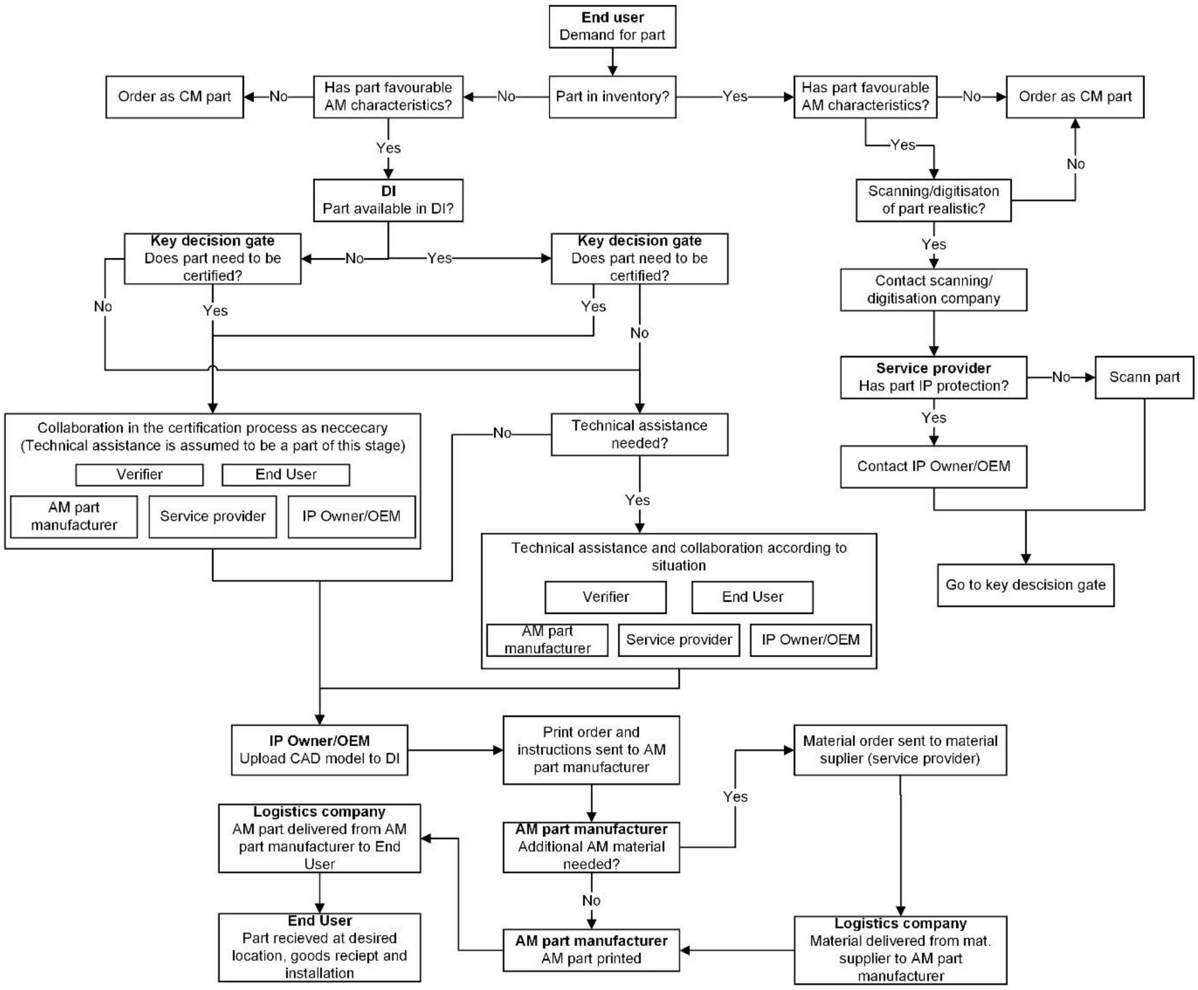

Figure 8. DI SP Decision model. Decision model visualises various decisions concerning AM and DI.

The decision model in Figure 8 may also be adapted for scenarios where O&G operators intend to reduce inventory and add SP to a DI. Figure 9 shows a model based on the right-hand side of Figure 8, adopted for the inventory reduction scenarios. In Figure 9, the O&G operator determines which SPs from inventory they want a scanning service provider to consider. In this scenario, the “No” option could be interpreted as a given SP having characteristics making it unsuitable for AM. Consequently, the SPs is better suited for buying as a CM SP. The same conclusion could be drawn if scanning the SP is unrealistic because of economic factors or technical limitations. Should the SP both have favourable AM characteristics and scanning of the SPs be viable, a check whether the SP is covered by IP protection. If any existing IP protections do not cover the SP, one could assess whether the SPs needs certification or technical assistance before the SPs is added to the DI. Otherwise, if the SPs is covered by IP protection, the best practice is to contact the IP owner, according to Company 2.

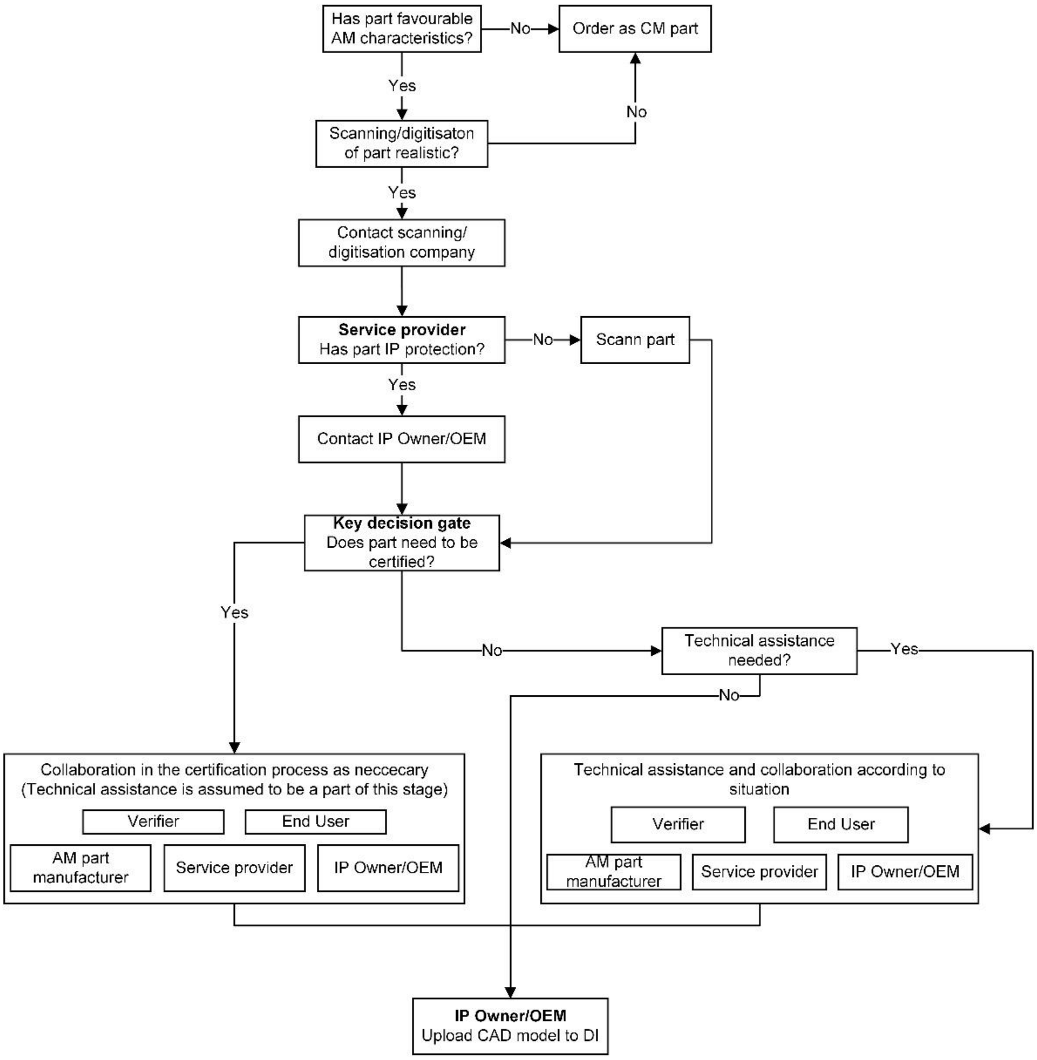

Figure 9. DI Ecosystem Inventory Reduction Decision Model

It is worth noting that the models are only simplified visualisations of critical decisions mentioned by the interviewed participants combined with academic literature. Also, certain scenarios have not been fully illustrated for simplicity's sake, such as recycling and repair of SPs. Certain stages might be more beneficial to execute at different points in the model. The model should be interpreted as an initial collection of what current actors in the DI ecosystem have highlighted as necessary, supported with insight from academic literature.

In summary, the decision model addresses RQ 3 by providing a model which may be used to assess alignment with existing procurement processes and IM strategies. There are many decisions and stages between a demand arising and receiving an AM SP through the DI ecosystem. As such, procurement workflows must be capable of handling the need for extensive communication and collaboration between many different actors at various points in time. Further, expedient processes will be necessary to enable on-demand manufacturing. Therefore, the decision model may be used to identify potential areas in existing IM strategies that may not align with the demands of SP management in a DI ecosystem.

The next chapter will conclude the thesis. The conclusion will summarise the thesis' scope, the methodological framework used to answer the RQs, the main findings from interviews and the discussion sections. Finally, a set of managerial implications and recommendations will be presented.

5 Conclusion

The main aim of the thesis was to assess how Norwegian O&G operators could implement DI as a SPs of a larger IM strategy. Seven companies identified as relevant by Vår Energi ASA were interviewed using a semi-structured interview format. The interviews provided valuable insight towards understanding how DI ecosystem's function. Also, information from interviews was used to describe the status, barriers and opportunities related to DI from an IM perspective. Other essential aspects for enabling the implementation of DI, such as ERP integration and identification of parts suitable for AM in inventories, were discussed. Finally, two decision models for SP management were presented based on the interview participants description of how the DI will function and key aspects identified by academic literature.

It was found that all participants essentially share the same vision of what DI is, its required functions, and the potential impact DI can have on O&G operators' inventories. The DI ecosystem envisioned by participants was compared with examples from academic literature. It was determined that the current structure of the DI has the potential to support the ambitions of enabling inventory reductions and on-demand manufacturing. The participants describe a DI ecosystem where the DI is independently operated with companies providing relevant services such as certification, AM printing, and technical assistance. Significant importance was placed on communication, collaboration and formation of local hubs supporting distributed production of AM SP.

The interviews provided information regarding some of the challenges experienced by companies in a DI ecosystem. The most notable challenges were the lack of commercial models ensuring attractive commercial conditions for OEMs and inefficient procurement processes. These challenges must be overcome for O&G operators to capitalise on the potential SC gains from DI. As such, commercial models making DI an attractive business proposition for OEMs must be developed. Also, current procurement processes should be aligned with the potentially increased requirement of communication and collaboration in DI ecosystems.

The findings highlighted in the thesis have some managerial implications for O&G operators. Participants and academic literature identified integration between DIs and ERP as a crucial enabler for IM implementation. In this regard, companies that already have achieved integration highlight the importance of ease of use and alignment with existing planning and procurement processes. Emphasis should be placed on facilitating easy access to AM parts in the DI. Ease-of-use would reduce the potential for internal resistance to change by making existing processes easier for employees than before. As such, involving relevant stakeholders in the integration process is highly important. Company 7 avoided integrating directly into their ERP due to high integration complexity. Instead, the DI was integrated into procurement software already integrated with the ERP. Considering that Company 1 mentioned O&G operators use different versions of the same ERP system, SC managers may assess the complexity related to integrating their own ERP version.

Implementation of DI may be used to reduce physical inventories by analysing AM suitability for parts currently stored in physical inventories. Generally, parts suitable for AM are characterised by infrequent demand, small order batches, high value, high design complexity and high supply chain risk. Two frameworks for assessing physical inventories for determining AM SPs suitability were presented. Managers may utilise the framework by Lindemann et al., (2015) to involve relevant organisational stakeholders in the selection process. Further, the framework presented by Knofius et al. (2016) could be adapted to incorporate SP material data from the company's ERP system into the selection process. By combining the two frameworks' managers may be able to consider organisational, strategic, and financial goals in the selection process while also considering a larger number of parts due to the incorporation of SP material data. Notable challenges in determining which parts are suitable for AM are the number of items stored in inventory, poor data quality and organisational goals.

There are certain limitations associated with the findings in the thesis. First, AM and DI are relatively new concepts for academics and practitioners. The limited knowledge practitioners possess were demonstrated by the lack of information regarding concrete measures companies could enact to use DI as a SPs of their inventories. Also, the academic literature has not provided any case studies where DI has been implemented in companies and documented its effectiveness. Another potential limitation could be the influence of participants being informed that Vår Energi ASA has contributed to developing the scope of the thesis. Additionally, while the interviewed companies reflect most of the DI ecosystem's envisioned functions, the sample size is relatively small. It should be expected that some of the limitations will be addressed as AM and DI gain maturity.

Future studies could provide an updated assessment of AM and DI usage in the O&G industry once actors have more experience. Studies could develop more detailed assessments of how the ecosystem interacts and operate. Another area deserving of more attention is the development of commercial models in the DI ecosystem. Future studies could further investigate the commercial models required for the ecosystem to be an attractive business.

6 Bibliography

Abdulhameed, O., Al-Ahmari, A., Ameen, W., & Mian, S. H. (2019). Additive manufacturing: Challenges, trends, and applications. *Advances in Mechanical Engineering*, *11*(2), 168781401882288. https://doi.org/10.1177/1687814018822880

Akindipe, O. S. (2014). Inventory Management—A Tool for Optimal Use of Resources and Overall Efficiency in Manufacturing SMEs. *Journal of Entrepreneurship, Management and Innovation*, *10*(4), 93–113. https://doi.org/10.7341/20141044

Alfares, H. K., & Ghaithan, A. M. (2016). Inventory and pricing model with price-dependent demand, time-varying holding cost, and quantity discounts. *Computers & Industrial Engineering*, *94*, 170–177. https://doi.org/10.1016/j.cie.2016.02.009

Andrade, C. (2021). The Inconvenient Truth About Convenience and Purposive Samples. *Indian Journal of Psychological Medicine*, *43*(1), 86–88. https://doi.org/10.1177/0253717620977000

Araújo, N., Pacheco, V., & Costa, L. (2021). Smart Additive Manufacturing: The Path to the Digital Value Chain. *Technologies*, *9*(4), 88. https://doi.org/10.3390/technologies9040088

Arbabian, M. E. (2022). Supply Chain Coordination via Additive Manufacturing. *International Journal of Production Economics*, *243*, 108318. https://doi.org/10.1016/j.ijpe.2021.108318

Aro-Gordon, S., & Gupte, J. (2016). Review of Modern Inventory Management Techniques. *Global Journal of Business & Management*, *1*(2).

Attaran, M. (2020). Digital technology enablers and their implications for supply chain management. *Supply Chain Forum: An International Journal*, *21*(3), 158–172. https://doi.org/10.1080/16258312.2020.1751568

Ballardini, R. M., Flores Ituarte, I., & Pei, E. (2018). Printing spare parts through additive manufacturing: Legal and digital business challenges. *Journal of Manufacturing Technology Management*, *29*(6), 958–982. https://doi.org/10.1108/JMTM-12-2017-0270

Barbosa, W. S., Gouvea, F. C., Martins, A. R. F. A., Belmonte, S. L. R., & Wanderley, R. F. F. (2022). Development of Spare-Parts Process Chain in Oil & Gas Industry Using Industry 4.0 Concepts. *International Journal of Engineering and Technology*, *14*(2), 9–14. https://doi.org/10.7763/IJET.2022.V14.1194

Baumers, M., & Holweg, M. (2019). On the economics of additive manufacturing: Experimental findings. *Journal of Operations Management*, *65*(8), 794–809. https://doi.org/10.1002/joom.1053

Bortolotti, T., Danese, P., & Romano, P. (2013). Assessing the impact of just-in-time on operational performance at varying degrees of repetitiveness. *International Journal of Production Research*, *51*(4), 1117–1130. https://doi.org/10.1080/00207543.2012.678403

Bourell, D., Kruth, J. P., Leu, M., Levy, G., Rosen, D., Beese, A. M., & Clare, A. (2017). Materials for additive manufacturing. *CIRP Annals*, *66*(2), 659–681. https://doi.org/10.1016/j.cirp.2017.05.009

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., … Walker, K. (2020). Purposive sampling: Complex or simple? Research case examples. *Journal of Research in Nursing*, *25*(8), 652–661. https://doi.org/10.1177/1744987120927206

Cardeal, G., Ferreira, B., Peças, P., Leite, M., & Ribeiro, I. (2022). Designing Sustainable Business Models to Reduce Spare Part Inventory. *Procedia CIRP*, *105*, 171–176. https://doi.org/10.1016/j.procir.2022.02.029

Cardeal, G., Sequeira, D., Mendonça, J., Leite, M., & Ribeiro, I. (2021). Additive manufacturing in the process industry: A process-based cost model to study life cycle cost and the viability of additive manufacturing spare parts. *Procedia CIRP*, *98*, 211–216. https://doi.org/10.1016/j.procir.2021.01.032

Carter, N., Bryant-Lukosius, D., DiCenso, A., Blythe, J., & Neville, A. J. (2014). The Use of Triangulation in Qualitative Research. *Oncology Nursing Forum*, *41*(5), 545–547. https://doi.org/10.1188/14.ONF.545-547

Cestana, A., Pastore, E., Alfieri, A., & Matta, A. (2019). Reducing resupply time with additive manufacturing in spare part supply chain. *IFAC-PapersOnLine*, *52*(13), 577–582. https://doi.org/10.1016/j.ifacol.2019.11.220

Chandima Ratnayake, R. M., Keprate, A., & Wdowik, R. (2019). Architecture for Digital Spare-Parts Library: Use of Additive Layer Manufacturing in the Petroleum Industry. In F. Ameri, K. E. Stecke, G. von Cieminski, & D. Kiritsis (Eds.), *Advances in Production Management Systems. Production Management for the Factory of the Future* (pp. 537–545). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-30000-5_66

Chaudhuri, A., Gerlich, H. A., Jayaram, J., Ghadge, A., Shack, J., Brix, B. H., … Ulriksen, N. (2021). Selecting spare parts suitable for additive manufacturing: A design science approach. *Production Planning & Control*, *32*(8), 670–687. https://doi.org/10.1080/09537287.2020.1751890

Chebet, E., & Kitheka, D. S. (2019). *Effects of Inventory Management System on Firm Performance – An Empirical Study*. *4*(9).

Chekurov, S., Metsä-Kortelainen, S., Salmi, M., Roda, I., & Jussila, A. (2018). The perceived value of additively manufactured digital spare parts in industry: An empirical investigation. *International Journal of Production Economics*, *205*, 87–97. https://doi.org/10.1016/j.ijpe.2018.09.008

Chekurov, S., Salmi, M., Verboeket, V., Puttonen, T., Riipinen, T., & Vaajoki, A. (2021). Assessing industrial barriers of additively manufactured digital spare part implementation in the machine-building industry: A cross-organizational focus group interview study. *Journal of Manufacturing Technology Management*, *32*(4), 909–931. https://doi.org/10.1108/JMTM-06-2020-0239

Chiu, M.-C., & Lin, Y.-H. (2016). Simulation based method considering design for additive manufacturing and supply chain: An empirical study of lamp industry. *Industrial Management & Data Systems*, *116*(2), 322–348. https://doi.org/10.1108/IMDS-07-2015-0266

De La Torre, N., Espinosa, M. M., & Domínguez, M. (2016). Rapid Prototyping in Humanitarian Aid To Manufacture Last Mile Vehicles Spare Parts: An Implementation Plan: Rapid Prototyping in Humanitarian Aid. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *26*(5), 533–540. https://doi.org/10.1002/hfm.20672

Dilberoglu, U. M., Gharehpapagh, B., Yaman, U., & Dolen, M. (2017). The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manufacturing*, *11*, 545–554. https://doi.org/10.1016/j.promfg.2017.07.148

Do, N. (2017). Integration of design and manufacturing data to support personal manufacturing based on 3D printing services. *The International Journal of Advanced Manufacturing Technology*, *90*(9–12), 3761–3773. https://doi.org/10.1007/s00170-016-9688-8

Equinor ASA. (n.d.). 3D printing and metal additive manufacturing (AM). Retrieved from https://www.equinor.com/energy/3d-printing

Esmaeilian, B., Behdad, S., & Wang, B. (2016). The evolution and future of manufacturing: A review. *Journal of Manufacturing Systems*, *39*, 79–100. https://doi.org/10.1016/j.jmsy.2016.03.001

Faludi, J., Van Sice, C. M., Shi, Y., Bower, J., & Brooks, O. M. K. (2019). Novel materials can radically improve whole-system environmental impacts of additive manufacturing. *Journal of Cleaner Production*, *212*, 1580–1590. https://doi.org/10.1016/j.jclepro.2018.12.017

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

González-Varona, J. M., Poza, D., Acebes, F., Villafáñez, F., Pajares, J., & López-Paredes, A. (2020). New Business Models for Sustainable Spare Parts Logistics: A Case Study. *Sustainability*, *12*(8), 3071. https://doi.org/10.3390/su12083071

Gupta, N., Tiwari, A., Bukkapatnam, S. T. S., & Karri, R. (2020). Additive Manufacturing Cyber-Physical System: Supply Chain Cybersecurity and Risks. *IEEE Access*, *8*, 47322–47333. https://doi.org/10.1109/ACCESS.2020.2978815

Hnaien, F., Dolgui, A., & Wu, D. D. (2016). Single-period inventory model for one-level assembly system with stochastic lead times and demand. *International Journal of Production Research*, *54*(1), 186–203. https://doi.org/10.1080/00207543.2015.1066518

Holmström, J., Partanen, J., Tuomi, J., & Walter, M. (2010). Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. *Journal of Manufacturing Technology Management*, *21*(6), 687–697. https://doi.org/10.1108/17410381011063996

Inegbedion, H., Eze, S., Asaleye, A., & Lawal, A. (2019). Inventory Management and Organisational Efficiency. *The Journal of Social Sciences Research*, (53), 756–763. https://doi.org/10.32861/jssr.53.756.763

Javadian Kootanaee, A., Babu, K. N., & Talari, H. F. (2013). Just-In-Time Manufacturing System: From Introduction to Implement. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2253243

Javaid, M., & Haleem, A. (2018). Additive manufacturing applications in medical cases: A literature based review. *Alexandria Journal of Medicine*, *54*(4), 411–422. https://doi.org/10.1016/j.ajme.2017.09.003

Kallio, H., Pietilä, A.-M., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in Industry*, *65*(1), 50–63. https://doi.org/10.1016/j.compind.2013.07.008

Khajavi, S. H., Salmi, M., & Holmström, J. (2020). Additive Manufacturing as an Enabler of Digital Spare Parts. In D. Eyers (Ed.), *Managing 3D Printing* (pp. 45–60). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-23323-5_4

Khalid, M., & Peng, Q. (2021). Sustainability and Environmental Impact of Additive Manufacturing: A Literature Review. *Computer-Aided Design and Applications*, *18*(6), 1210–1232. https://doi.org/10.14733/cadaps.2021.1210-1232

Knofius, N., van der Heijden, M. C., Sleptchenko, A., & Zijm, W. H. M. (2021). Improving effectiveness of spare parts supply by additive manufacturing as dual sourcing option. *OR Spectrum*, *43*(1), 189–221. https://doi.org/10.1007/s00291-020-00608-7

Knofius, N., van Der Heijden, M. C., & Zijm, W. H. M. (2016). Selecting parts for additive manufacturing in service logistics. *Journal of Manufacturing Technology Management*, *27*(7), 915–931. https://doi.org/10.1108/JMTM-02-2016-0025

Kortabarria, A., Apaolaza, U., Lizarralde, A., & Amorrortu, I. (2018). Material management without forecasting: From MRP to demand driven MRP. *Journal of Industrial Engineering and Management*, *11*(4), 632. https://doi.org/10.3926/jiem.2654

Kostić, K. (2009). Inventory control as a discrete system control for the fixed-order quantity system. *Applied Mathematical Modelling*, *33*(11), 4201–4214. https://doi.org/10.1016/j.apm.2009.03.004

Kostidi, E., Nikitakos, N., & Progoulakis, I. (2021). Additive Manufacturing and Maritime Spare Parts: Benefits and Obstacles for the End-Users. *Journal of Marine Science and Engineering*, *9*(8), 895. https://doi.org/10.3390/jmse9080895

Kunovjanek, M., Knofius, N., & Reiner, G. (2022). Additive manufacturing and supply chains – a systematic review. *Production Planning & Control*, *33*(13), 1231–1251. https://doi.org/10.1080/09537287.2020.1857874

Lastra, R., Pereira, A., Díaz-Cacho, M., Acevedo, J., & Collazo, A. (2022). Spare Parts Made by Additive Manufacturing to Improve Preventive Maintenance. *Applied Sciences*, *12*(20), 10564. https://doi.org/10.3390/app122010564

Li, C., & Scheller-Wolf, A. (2011). Push or Pull? Auctioning Supply Contracts: Push or Pull? Auctioning Supply Contracts. *Production and Operations Management*, *20*(2), 198–213. https://doi.org/10.1111/j.1937-5956.2010.01174.x

Li, N., Huang, S., Zhang, G., Qin, R., Liu, W., Xiong, H., … Blackburn, J. (2019). Progress in additive manufacturing on new materials: A review. *Journal of Materials Science & Technology*, *35*(2), 242–269. https://doi.org/10.1016/j.jmst.2018.09.002

Lindemann, C., Reiher, T., Jahnke, U., & Koch, R. (2015). Towards a sustainable and economic selection of part candidates for additive manufacturing. *Rapid Prototyping Journal*, *21*(2), 216–227. https://doi.org/10.1108/RPJ-12-2014-0179

Liu, L., Xu, H., & Zhu, S. X. (2020). Push verse pull: Inventory-leadtime tradeoff for managing system variability. *European Journal of Operational Research*, *287*(1), 119–132. https://doi.org/10.1016/j.ejor.2020.04.033

Liu, P., Huang, S. H., Mokasdar, A., Zhou, H., & Hou, L. (2014). The impact of additive manufacturing in the aircraft spare parts supply chain: Supply chain operation reference (scor) model based analysis. *Production Planning & Control*, *25*(13–14), 1169–1181. https://doi.org/10.1080/09537287.2013.808835

Mahmood, F., Khan, A. Z., & Bokhari, R. H. (2019). ERP issues and challenges: A research synthesis. *Kybernetes*, *49*(3), 629–659. https://doi.org/10.1108/K-12-2018-0699

Manogharan, G., Wysk, R. A., & Harrysson, O. L. A. (2016). Additive manufacturing–integrated hybrid manufacturing and subtractive processes: Economic model and analysis. *International Journal of Computer Integrated Manufacturing*, *29*(5), 473–488. https://doi.org/10.1080/0951192X.2015.1067920

Matthes, F., Schulz, C., & Haller, K. (2011). Testing & quality assurance in data migration projects. *2011 27th IEEE International Conference on Software Maintenance (ICSM)*, 438–447. Williamsburg, VA, USA: IEEE. https://doi.org/10.1109/ICSM.2011.6080811

Mecheter, A., Pokharel, S., & Tarlochan, F. (2022). Additive Manufacturing Technology for Spare Parts Application: A Systematic Review on Supply Chain Management. *Applied Sciences*, *12*(9), 4160. https://doi.org/10.3390/app12094160

Mellor, S., Hao, L., & Zhang, D. (2014). Additive manufacturing: A framework for implementation. *International Journal of Production Economics, 149,* 194–201. https://doi.org/10.1016/j.ijpe.2013.07.008

Metsä-Kortelainen, S., Reijonen, J., Riipinen, T., & Vaajoki, A. (2020). *New business from digital spare parts*. FI: VTT Technical Research Centre of Finland. Retrieved from https://doi.org/10.32040/2020.978-951-38-8827-5

Montero, J., Weber, S., Bleckmann, M., & Paetzold, K. (2020). A methodology for the decentralised design and production of additive manufactured spare parts. *Production & Manufacturing Research*, *8*(1), 313–334. https://doi.org/10.1080/21693277.2020.1790437

Naghshineh, B., & Carvalho, H. (2022). The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review. *International Journal of Production Economics*, *247*, 108387. https://doi.org/10.1016/j.ijpe.2021.108387

Nawanir, G., Kong Teong, L., & Norezam Othman, S. (2013). Impact of lean practices on operations performance and business performance: Some evidence from Indonesian manufacturing companies. *Journal of Manufacturing Technology Management*, *24*(7), 1019–1050. https://doi.org/10.1108/JMTM-03-2012-0027

Oluwaseyi, J. A., Onifade, M. K., & Odeyinka, O. F. (2017). Evaluation of the Role of Inventory Management in Logistics Chain of an Organisation. *LOGI – Scientific Journal on Transport and Logistics*, *8*(2), 1–11. https://doi.org/10.1515/logi-2017-0011

Ott, K., Pascher, H., & Sihn, W. (2019). Improving sustainability and cost efficiency for spare part allocation strategies by utilisation of additive manufacturing technologies. *Procedia Manufacturing, 33*, 123–130. https://doi.org/10.1016/j.promfg.2019.05.001

Pasandideh, S. H. R., Niaki, S. T. A., & Nia, A. R. (2011). A genetic algorithm for vendor managed inventory control system of multi-product multi-constraint economic order quantity model. *Expert Systems with Applications*, *38*(3), 2708–2716. https://doi.org/10.1016/j.eswa.2010.08.060

Poles, R. (2013). System Dynamics modelling of a production and inventory system for remanufacturing to evaluate system improvement strategies. *International Journal of Production Economics*, *144*(1), 189–199. https://doi.org/10.1016/j.ijpe.2013.02.003

Powell, Daniel, Rennie, A. E. W., Geekie, L., & Burns, N. (2020). Understanding powder degradation in metal additive manufacturing to allow the upcycling of recycled powders. *Journal of Cleaner Production*, *268*, 122077. https://doi.org/10.1016/j.jclepro.2020.122077

Powell, Daryl. (2013). ERP systems in lean production: New insights from a review of lean and ERP literature. *International Journal of Operations & Production Management*, *33*(11/12), 1490–1510. https://doi.org/10.1108/IJOPM-07-2010-0195

Priniotakis, G., & Argyropoulos, P. (2018). Inventory management concepts and techniques. *IOP Conference Series: Materials Science and Engineering*, *459*, 012060. https://doi.org/10.1088/1757-899X/459/1/012060

Puchkova, A., Le Romancer, J., & McFarlane, D. (2016). Balancing Push and Pull Strategies within the Production System. *IFAC-PapersOnLine*, *49*(2), 66–71. https://doi.org/10.1016/j.ifacol.2016.03.012

Rahman, N. A. A., Sharif, S. M., & Esa, M. M. (2013). Lean Manufacturing Case Study with Kanban System Implementation. *Procedia Economics and Finance*, *7*, 174–180. https://doi.org/10.1016/S2212-5671(13)00232-3

Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, *102*, 214–224. https://doi.org/10.1016/j.techfore.2015.07.023

Robinson, O. C. (2014). Sampling in Interview-Based Qualitative Research: A Theoretical and Practical Guide. *Qualitative Research in Psychology*, *11*(1), 25–41. https://doi.org/10.1080/14780887.2013.801543

Rupp, M., Buck, M., Klink, R., Merkel, M., & Harrison, D. K. (2022). Additive manufacturing of steel for digital spare parts – A perspective on carbon emissions for decentral production. *Cleaner Environmental Systems*, *4*, 100069. https://doi.org/10.1016/j.cesys.2021.100069

Salmi, M., Partanen, J., Tuomi, J., Chekurov, S., Björkstrand, R., Huotilainen, E., … Mikkola, M. (2018). *Digital Spare Parts* (p. 65). Aalto University & VTT Technical Research Centre of Finland Ltd. Retrieved from Aalto University & VTT Technical Research Centre of Finland Ltd website: http://urn.fi/URN:ISBN:978-952-60-3746-2

Samaranayake, P. (2009). Business process integration, automation, and optimization in ERP: Integrated approach using enhanced process models. *Business Process Management Journal*, *15*(4), 504–526. https://doi.org/10.1108/14637150910975516

Singh, D., & Verma, A. (2018). Inventory Management in Supply Chain. *Materials Today: Proceedings*, *5*(2), 3867–3872. https://doi.org/10.1016/j.matpr.2017.11.641

Sireesha, M., Lee, J., Kranthi Kiran, A. S., Babu, V. J., Kee, B. B. T., & Ramakrishna, S. (2018). A review on additive manufacturing and its way into the oil and gas industry. *RSC Advances*, *8*(40), 22460–22468. https://doi.org/10.1039/C8RA03194K

Song, J.-S., & Zhang, Y. (2020). Stock or Print? Impact of 3-D Printing on Spare Parts Logistics. *Management Science*, *66*(9), 3860–3878. https://doi.org/10.1287/mnsc.2019.3409

Sundar, R., Balaji, A. N., & Kumar, R. M. S. (2014). A Review on Lean Manufacturing Implementation Techniques. *Procedia Engineering*, *97*, 1875–1885. https://doi.org/10.1016/j.proeng.2014.12.341

Thomas, D. (2016). Costs, benefits, and adoption of additive manufacturing: A supply chain perspective. *The International Journal of Advanced Manufacturing Technology*, *85*(5–8), 1857–1876. https://doi.org/10.1007/s00170-015-7973-6

Togwe, T., Eveleigh, T. J., & Tanju, B. (2019). An Additive Manufacturing Spare Parts Inventory Model for an Aviation Use Case. *Engineering Management Journal*, *31*(1), 69–80. https://doi.org/10.1080/10429247.2019.1565618

Tom Jose, V., Jayakumar, A., & Sijo, M. T. (2013). Analysis of Inventory Control Techniques; A Comparative Study. *International Journal of Scientific and Research Publications*, *3*(3).

Vår Energi ASA. (2022). *Vår Energi Annual report 2022*. Retrieved from https://investors.varenergi.no/reports-and-presentations/default.aspx

Verboeket, V., & Krikke, H. (2019). The disruptive impact of additive manufacturing on supply chains: A literature study, conceptual framework and research agenda. *Computers in Industry*, *111*, 91–107. https://doi.org/10.1016/j.compind.2019.07.003

Watson, J. K., & Taminger, K. M. B. (2018). A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption. *Journal of Cleaner Production*, *176*, 1316–1322. https://doi.org/10.1016/j.jclepro.2015.12.009

Westerweel, B., Basten, R. J. I., & van Houtum, G.-J. (2018). Traditional or Additive Manufacturing? Assessing Component Design Options through Lifecycle Cost Analysis. *European Journal of Operational Research*, *270*(2), 570–585. https://doi.org/10.1016/j.ejor.2018.04.015

Williams, B. D., & Tokar, T. (2008). A review of inventory management research in major logistics journals: Themes and future directions. *The International Journal of Logistics Management*, *19*(2), 212–232. https://doi.org/10.1108/09574090810895960

Wits, W. W., García, J. R. R., & Becker, J. M. J. (2016). How Additive Manufacturing Enables more Sustainable End-user Maintenance, Repair and Overhaul (MRO) Strategies. *Procedia CIRP*, *40*, 693–698. https://doi.org/10.1016/j.procir.2016.01.156

Wong, K. V., & Hernandez, A. (2012). A Review of Additive Manufacturing. *ISRN Mechanical Engineering*, *2012*, 1–10. https://doi.org/10.5402/2012/208760

Yang, L., Cai, G., & Chen, J. (2018). Push, pull, and supply chain risk-averse attitude. *Production and Operations Management*, *27*(8), 1534–1552.

Zanoni, S., Ashourpour, M., Bacchetti, A., Zanardini, M., & Perona, M. (2019). Supply chain implications of additive manufacturing: A holistic synopsis through a collection of case studies. *The International Journal of Advanced Manufacturing Technology*, *102*(9–12), 3325–3340. https://doi.org/10.1007/s00170-019-03430-w

Zhang, Yuan, Jedeck, S., Yang, L., & Bai, L. (2019). Modeling and analysis of the on-demand spare parts supply using additive manufacturing. *Rapid Prototyping Journal*, *25*(3), 473–487. https://doi.org/10.1108/RPJ-01-2018-0027

Zhang, Yue, Westerweel, B., Basten, R., & Song, J.-S. (2022). Distributed 3D Printing of Spare Parts via IP Licensing. *Manufacturing & Service Operations Management*, *24*(5), 2685–2702. https://doi.org/10.1287/msom.2022.1117

Ziukov, S. (2015). A literature review on models of inventory management under uncertainty. *Business Systems & Economics*, *5*(1), 26. https://doi.org/10.13165/VSE-15-5-1-03