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The influence of digital inventory and on-demand manufacturing business models on sustainable spare parts management

A case from Norwegian Oil and Gas industry

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Industrial Asset Management

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I

Abstract

The present thesis investigates the multifaceted influence of Digital inventories and on-demand manufacturing business models on spare parts management toward realizing the sustainable development opportunities. Additive manufacturing is well established manufacturing method and have been used for various purposes in the industries for decades. Moreover, due to technological maturity of AM, extensive AM adoption becomes a viable choice in the industry to increase the responsiveness of supply chain and enhance the efficiency of the spare parts management operations. This industrial landscape contributed to the emergence of Digital inventories to store digital spare parts and facilitate on demand manufacturing.

However, studies analyzing the attributes of digital inventories and their impact on spare parts management are quite limited in the literature. In addition, industrial developments in the business ecosystem raise questions about the governance of digital inventory platforms, which require further systematic analysis. Moreover, within the context of the Norwegian O&G industry, it is also critical to explore the opportunities these technologies present for sustainable value creation in the sector.

The literature review and interviews highlighted the promise of DIs and on demand manufacturing to facilitate the transition from mass production to mass customization, reducing physical inventories, of spare parts as a means to address sustainability challenges, and enhancing the operational efficiency requirements of the Norwegian O&G industry.

Additionally, the interviews highlighted several key findings, including that DIs can effectively act as a digital hub to commercialize digital spare parts and enhance coordination among stakeholders. This facilitates new digital business models, incorporating licensing for digital spare parts, benefiting both OEMs and operators. It also helps stabilize revenue for AM suppliers against the high upfront costs of qualification processes and drives demand in the AM market. The findings underscore the necessity for operators to engage more effectively by identifying suitable parts for AM and highlight the need for a cultural change among stakeholders to embrace new technologies and strategic planning methods, ultimately contributing to building a robust, dynamic value network.

Acknowledgements

This thesis represents the final part of my studies in industrial asset management, fulfilling the final requirement for my master's degree. An academic journey that has enabled me to develop myself in ways I always aspired to. I am filled with joy that as a result of this journey, I have received the invaluable gift of an endless desire to learn more. Writing this thesis has been an interesting yet challenging journey, filled with hard work and curiosity. Also, my achievement is the compound effect of many who helped me through the process, thus, I have many thanks to give:

First, I want to acknowledge Moreld Apply for providing me with an interesting and stimulating topic. I sincerely thank my professor, academic supervisor, and mentor, Jawad Raza, for his commitment to guiding me whenever I faced a challenge. His extensive knowledge and experience in the oil and gas industry provided me with professional mentorship through his practical recommendations. Therefore, this thesis has benefited greatly from his invaluable guidance and support. I am privileged to have had you as my supervisor and teacher.

A special honor and thanks to my industrial supervisor, Jørgen Grønsund. Your commitment to my work and your support have been a cornerstone of this study. Our many inspiring and constructive discussions provided firsthand knowledge about Digital inventories, and your sophisticated viewpoints taught me critical thinking. I am sincerely grateful for your mentorship and guidance.

I want to extend my gratitude to Vigdis B. Holst at Moreld Apply and Idriss El-Thalji, my professor at UiS, who immensely contributed to my understanding of the multifaceted nature of Digital inventories. Their guidance, particularly during the initial phases of my thesis, was essential in shaping the direction of this study.

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Stavanger, 15 June 2024
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Table of Contents

1- Introduction 1
  1-1 Topic Background 1
  1-2 Problem description 3
  1-3 Thesis objectives 5
  1-4 Methodology 6
  1-5 Thesis structure outline 6
2- Methodology 8
  2-1 Design and approach 8
  2-2 Data Collection Methods 9
  2-3 Data Analysis and Validation 10
3- Contextual Background 12
4- Theoretical Background 16
  4-1 Asset management 16
  4-2 Inventory management 20
  4-3 Spare parts management 21
  4-4 Additive manufacturing 26
  4-5 Digital business models 28
  4-6 Digital platforms 30
  4-7 The concept of Digital inventory platforms 34
  4-8 On-demand manufacturing 39
  4-9 Sustainability 44
  4-10 New technologies 48
5- Data Collection & Analysis 51
  5-1 Data Collection 51
  5-2 Analysis & result 54
    5-2-1 Spare parts management and AM 56
    5-2-2 Digital Inventory platforms 62
    5-2-3 On demand manufacturing 70
    5-2-4 Sustainable development 77
6- Discussion 85
  6-1 Spare parts management and AM 85
  6-2 Digital inventory and on demand manufacturing business models 87

6-3 Governance for Digital inventory platforms....................98
7- Conclusion....................104
8- References....................110
A Appendices....................119
A-1 Interview guide....................119
A-2 Python code sample....................121

List of Figures

Figure 1- 3D printing market growth and forecast (Proto Labs, 2024) 2
Figure 2- Methodology design and approach 8
Figure 3- Value creation from the NCS (The Shelf in 2022, n.d.) 12
Figure 4- Production levels on the NCS (The Shelf in 2022, n.d.) 13
Figure 5- Relationship between key terms (International Organization for Standardization, 2014) 18
Figure 6- Elements of integrated spare parts management. (Bacchetti & Saccani, 2012)........... 22
Figure 7- Centralized and decentralized formations of DIs 38
Figure 8- Circular Economy vs Linear Economy (Dev, 2024) 46
Figure 9- Advantages of implementing Digital Product Passport 50
Figure 10- Participants' experience range 53
Figure 11- Preference for spare part for DI and 3D printing 61
Figure 12- Preference for DI formation – Information management 67
Figure 13- Preference for DI formation – Qualification process 73
Figure 14- Preference for DI formation – Cluster of 3D manufacturers 77
Figure 15- Current customization level of spare parts 80
Figure 16- Preference for DI formation – Achieving sustainable outcomes 83

List of Tables

Table 1- Spare parts categories and correspondent value based on NORSOK Z-088 (Husum, Leirvaag, & El-Thalji, 2022, p.3) 24
Table 2- Comparison between centralized and decentralized governance structures 34
Table 3- Key attributes of Digital inventory platforms 37
Table 4- AM-related standards established by DNV. 41
Table 5- Participants' characteristics 53

List of acronyms

AI = Artificial Intelligence

AM = Additive Manufacturing

API = American Petroleum Institute

API = Application Programming Interface

Capex = Capital Expenses

CM = Conventional Manufacturing

DI = Digital Inventory

DPP = Digital Product Passport

IPR = Intellectual Property Right

IT = Information Technology

M&M = Modification and Maintenance

NCS = Norwegian Continental Shelf

O&G = Oil and Gas

OEM = Original Equipment Manufacturer

Opex = Operational Expenses

OT = Operational Technology

PLM = Product Lifecycle Management

SPIR = Spare Part Interchangeability Record

"Management means the substitution of thought for muscle, of knowledge for folklore, and of cooperation for force."

Dr. Peter F. Drucker

1- Introduction

(Everett, 2013) suggests that a good master's thesis introduction should encompass the thesis topic, problem definition, methodology, main objectives, and the thesis structure. This introduction aligns with Everett and Furseth's guidelines, providing a comprehensive overview of the thesis content.

This thesis is a project written at the University of Stavanger in collaboration with the company Moreld Apply AS. The company is a leading multi-disciplinary engineering firm specializing in contract management throughout all project phases, from conceptual development and studies to completion, commissioning, and decommissioning. It offers a broad range of services, including operations, maintenance, and modifications of O&G production facilities on the NCS. (*Apply*, n.d.)

1-1 Topic Background

Digitalization profoundly has impacted the organizational processes and transforms the communication patterns between businesses into a more agile and interconnected ecosystem. The O&G industry can benefit from adoption of new digital tools and new technologies to enhance the financial performance, customer value, and address sustainability issues in a systematic, efficient and effective manner.

In an era where the emerging business environment demands for increased reliability, agility and profitability and the performance boundaries are pushed in all industries, organizations are forced to reevaluate their strategic planning and adopt digital tools to enable them to progress based on having access to accurate and reliable data-driven insights of the performance of their assets.

These assets are subjected to increased production objectives, and they are expected to live longer with reliable performance, added by the increasing influence of environmental and social influence on the competition, these conditions expose organizations to a complex profile of opportunities and risks. (Liyanage, 2016)

Moreover, the key characteristics of the digital world are essentially related to improved communication, convergence of information, and seamless integration between the physical and digital worlds. (Haouel & Nemeslaki, 2023) Additive manufacturing (AM) is manufacturing method that relies on digital CAD files to produce physical parts by adding the material layer by layer, which is also known as a manufacturing method to facilitate the digital manufacturing. (Meier, 2020)

Furthermore, the AM technology, also known as 3D printing, has reached to a maturity level to produce end parts, as opposed to what it was merely used for prototyping in the past. Therefore, the industry is gradually considering the viability of larger scale of AM implementation, particularly for spare parts to enable AM suppliers to manufacture and send parts on an on-demand basis and near the end users. (Naghshineh et al., 2023)

According to PwC Strategy report on the future opportunities and challenges of 3D printing for spare parts, it is mentioned that "3D printing will not transform the spare parts business immediately. But companies that do not begin investing in the capabilities and technologies needed, including in the supply chain, will find it difficult to catch up with first-moving competitors in the future." (Wunderlin et al., 2017)

Based on a recent market analysis conducted by Proto Labs, 70% of surveyed businesses printed more parts in 2023 than in 2022 and in addition, 82% of their research respondents expressed that 3D printing helped them save substantial costs. (Proto Labs, 2024)

Interestingly, the report also predicts the 3D printing market growth by the end of 2028 as it is portrayed in the following figure,

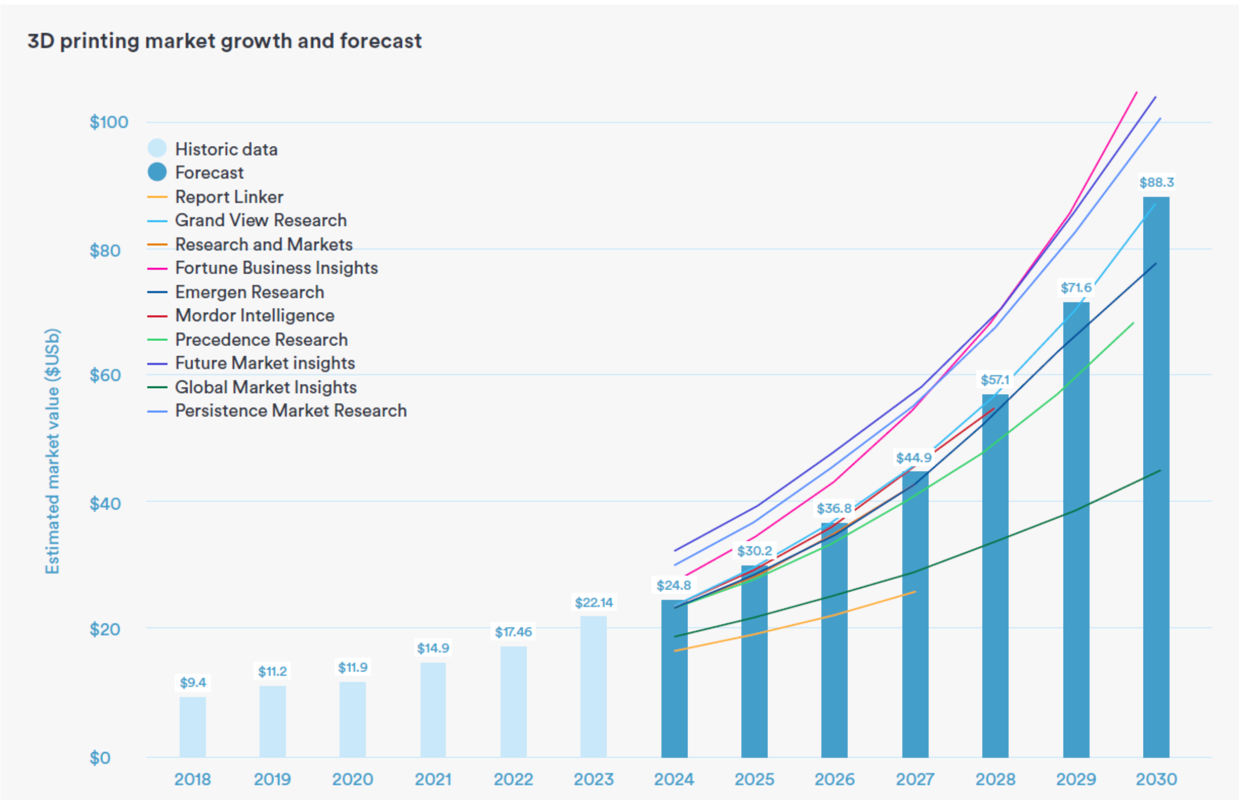

Figure 1- 3D printing market growth and forecast (Proto Labs, 2024)

This figure presents a summary of data from leading market analyst firms, assessing the 3D printing market in 2023. It includes revenues generated from 3D printing systems, software, materials, and services, while excluding internal corporate investments in 3D printing technologies. The data, sourced from publicly available information, offers an estimate of the current size and future potential of the global 3D printing market. (Proto Labs, 2024)

Thus, this market growth, which has been strongly expanding, is a clear sign for industrial firms to rethink about their supply chain strategy and adapt it to new market trends and performance requirements if they are interested to pursue opportunities and harvest on them to create competitive edge.

To harvest on these opportunities, the idea of digital inventories has emerged to store the digital spare parts and make them available for on demand production. According to (Ballardini et al., 2018), some OEMs (Original Equipment Manufacturer) started to create their own digital inventories where they keep their production design files to furthermore, sell certain parts to end users. However, the processes to handle the procurement of digital spare parts lack security and organization. Thus, (Ballardini et al., 2018) implied that there is a great interest in the industry to scale up these digital inventories to digital platforms to establish a better ground for on demand manufacturing of spare parts.

Therefore, DI platforms are essentially practical to enable on demand manufacturing of parts close to the end user premises, which can have several important advantages for the value chain, where the productivity can be increased, maintenance planning to ensure availability of the systems can be enhanced, while reducing costs for abroad transportations, reducing inventories, reducing reliance on foreign corporations and suppliers, can contribute to higher level of resilience in the industry.

These outcomes can have significant impacts on the sustainability profile of organizations with regards to spare parts management, and thus add value to the social legitimacy, reputation and profitability of organizations. Moreover, in accordance with recent studies, such as Circularity Gap report (CGR, 2022), "70% of greenhouse gas emissions are linked to material handling and use, and satisfying our needs and wants with fewer materials can have radical impacts." Added by (Cowger et al., 2024), "every 1% increase in consumer goods companies' plastic production is associated with a 1% increase in plastic pollution in the environment". Putting all these together, one can clearly see the vast amount of opportunities that AM technology can offer in this regard and the positive outcomes can potentially be manifolded or expedited by the proper utilization of DI platforms.

In this regard, new business models with new digitally and sustainability-oriented features can emerge and contribute to a dynamic and resilient value network. However, knowledge and technology readiness of organizations play a critical role in embracing the changes timely and properly to cope with modern industrial trends and being able to satisfy the ever-evolving customers' needs with more agility.

1-2 Problem description

Investigating the current status of spare parts management in the Norwegian O&G industry and utilization progression of AM and Digital inventories for spare parts provides practical information on how new strategies should be set to address the required changes to enhance the efficiency of the work processes and contribute to sustainability and circular economy in a larger scale.

According to a recent literature review on spare parts management, (Kulshrestha et al., 2024) expressed that, “More work needs to be undertaken in the field of integration of Industry 4.0 concepts with circularity to achieve sustainable value creation in the spare parts management.”

Moreover, an article titled, “The perceived value of additively manufactured digital spare parts in industry: An empirical investigation”, mentioned that the interest in providing services to produce digital spare parts is high in the industry, however, they realized that the practitioners believed that “neither the AM technology, nor the ICT infrastructure of the companies that would make digital spare parts distribution possible are robust enough for the digital distribution method to be deployed fully in the interviewed companies.” (Chekurov et al., 2018) Also added that the conceptual definition of digital spare parts is further required to be refined by reducing the complexity of the language. (Chekurov et al., 2018)

On the other hand, the literature on digital inventories is very limited as of today and the knowledge about different aspects of them are still very limited. Also, within the context of the Norwegian O&G industry, despite heavy investments and discussions about digital inventories since a few years ago, the DI platforms have not become fully operational, and the stored digital spare parts is still at very low level.

Therefore, it becomes interesting to investigate the current utilization status of DIs and on demand manufacturing of spare parts to respond to O&G operators, as leveraging this opportunity is key for the O&G industry to enhance resilience and sustainability.

Additionally, the various advantages of implementing AM technology and on-demand manufacturing have encouraged organizations to reassess their presence in the new business environment and reevaluate their strategic planning. This reassessment aims to position themselves for a competitive advantage in the current turbulent economy and highly competitive market.

Then it is practical to note that “strategic planning to confront the undefined future is very much dependent on the users’ perception about what is important, how those elements would evolve in the future, and linkages between elements in shaping the forces in the environment.” (Liyanage, 2016)

Thus, this thesis aims to investigate and delve into the realm of DIs and on-demand manufacturing utilization and their influence on spare parts management and its sustainability aspect. This goal is pursued by reviewing the available literature, to shape a better understanding of DI platforms, subsequently this is followed by a qualitative analysis through conduction of interviews with AM experts from various organizations, primarily those directly involved with the Norwegian O&G industry. Furthermore, expert responses are visualized to draw an industrial and reliable picture of DIs, seeking to provide a comprehensive analysis, highlighting the possibilities, opportunities, and challenges.

1-3 Thesis objectives

According to the problem definition, the following objectives were shaped to explore opportunities and challenges, review literature, and conduct a market survey. This begins with examining the nature of spare parts management and reporting on current industry challenges. A systemic approach will be used to understand the interconnectedness and interplays between inventory management and asset management.

The next step is to understand the relevance of AM for the production of spare parts and the concept of digital spare parts. This will be followed by exploring digital business models and platforms, focusing on the governance of digital platforms. The thesis aims to provide a comprehensive understanding of digital inventory platforms and their importance in integrating data and facilitating on-demand manufacturing of spare parts within the context of the Norwegian O&G industry.

Key conditions for on-demand manufacturing, such as qualification and licensing, will be discussed. The potential of these platforms to contribute to sustainable development will also be examined. Lastly, the thesis will briefly mention new technologies that can be seamlessly integrated with AM to enhance operational efficiency, reliability, and agility.

The goals of this master's thesis are to conduct a market survey to explore:

- Current spare parts management challenges and the suitability of spare parts based on NORSOK Z-008 for AM
- Attributes of digital inventories and their value to spare parts management.
- Modern conditions for on-demand manufacturing of spare parts
- Opportunities and challenges of centralized and decentralized digital inventories
- How digital inventories and on-demand manufacturing for spare parts can facilitate sustainable development in the Norwegian O&G industry

Thus, with regards to these objectives, a research question is shaped as:

- What are the impacts of utilization of digital inventories and on-demand manufacturing on spare parts management toward sustainable development?

The primary intention was to avoid conducting an organization-specific research paper, rather analyzing the AM ecosystem and utilization opportunities and challenges of DIs, while the scope is limited to the Norwegian O&G industry to achieve a prevailing thesis that can be utilized by most organizations within this sector.

1-4 Methodology

The methodology of this thesis is mixed approach, both incorporating qualitative, grounded in interpretivism through collecting data from conducting interviews and quantitative analysis based on the data gathered to visualize the result and present a more transparent and easier to navigate result to provide a better understanding of the impact of digital inventory platforms on spare parts management and sustainability within the context of Norwegian O&G industry.

This methodology approach found suitable as particularly the information about the DI platforms is quite limited in the literature and there has not been found through a specific study on the opportunities and challenges of the governance of DI platforms and their impacts on on-demand manufacturing of spare parts and the sustainability aspects of it. Thus, a thorough literature review is conducted to build a relevant and practical basis to furthermore connect the data collected from the interviews to enable a thorough analysis to provide a comprehensive understanding of the thesis objectives.

Furthermore, data analysis involved thematic analysis with NVivo software, Python for visualization and Excel for organizing the data to grasp the depth and full potential of the data collected from the interview participants and reflect them accurately. Reliability and credibility of analysis were also addressed through triangulation, comparing interview data with academic literature and consultation with experts to validate the findings.

To find more about the details of the methodology approach used in this thesis, please review the following chapter.

1-5 Thesis structure outline

Thesis outline is included to guide the readers into different chapters' contents and to facilitate their access to specific information. The thesis is composed of seven main chapters and a reference chapter, each chapter contains a small introduction of its content, and the structure of the thesis is as follows:

1. ***Introduction:*** This chapter presents an introduction to the master thesis
2. ***Methodology:*** This chapter will present the research design and methodology used to address the thesis objectives and the scope of the thesis.
3. ***Contextual background:*** This chapter will shed light on the critical role of the Norwegian O&G industry in Norway's economy value creation, discussing the importance of spare parts management and use of new technologies to enhance the associated operations
4. ***Theoretical background:*** This chapter reviews the literature on related topics such as asset management, AM, spare parts management, DI platforms etc.
5. ***Data collection & analysis:*** This chapter includes two sections, data collection and, analysis and result that in first section it discusses about the data collection details on how it is

conducted, the purposive sampling and summary on the characteristics of the interviewees, in the next section the analysis of the collected data into 4 sub-sections is addressed.

6. ***Discussion*****:** This chapter sums up and pulls together the main findings of the work discussing findings from interviews and academic literature.
7. ***Conclusion:*** This chapter gives the final remarks of this thesis in the form of a conclusion, together with areas for further studies
8. ***References***

2- Methodology

This chapter provides a comprehensive overview of the research methodology employed in this master's thesis. It includes a detailed explanation of the objectives, philosophy, approach, methodologies, data sources, and strategies utilized to guide the research process. The approach encompassed a comprehensive examination of existing literature and the gathering of qualitative data from operators, AM suppliers, OEMs, industrial consultancy firms, and other service providers. The qualitative data underwent a comprehensive analysis utilizing thematic analysis to identify themes and patterns that offer insights into the objectives of the study.

2-1 Design and approach

The fundamental research methodology used here is a mixed-methods approach, combining qualitative and quantitative analyses. The underlying philosophical approach is interpretivism, which supports the comprehensive, holistic, and systematic understanding of how digital inventory platforms influence spare parts management and its sustainability.

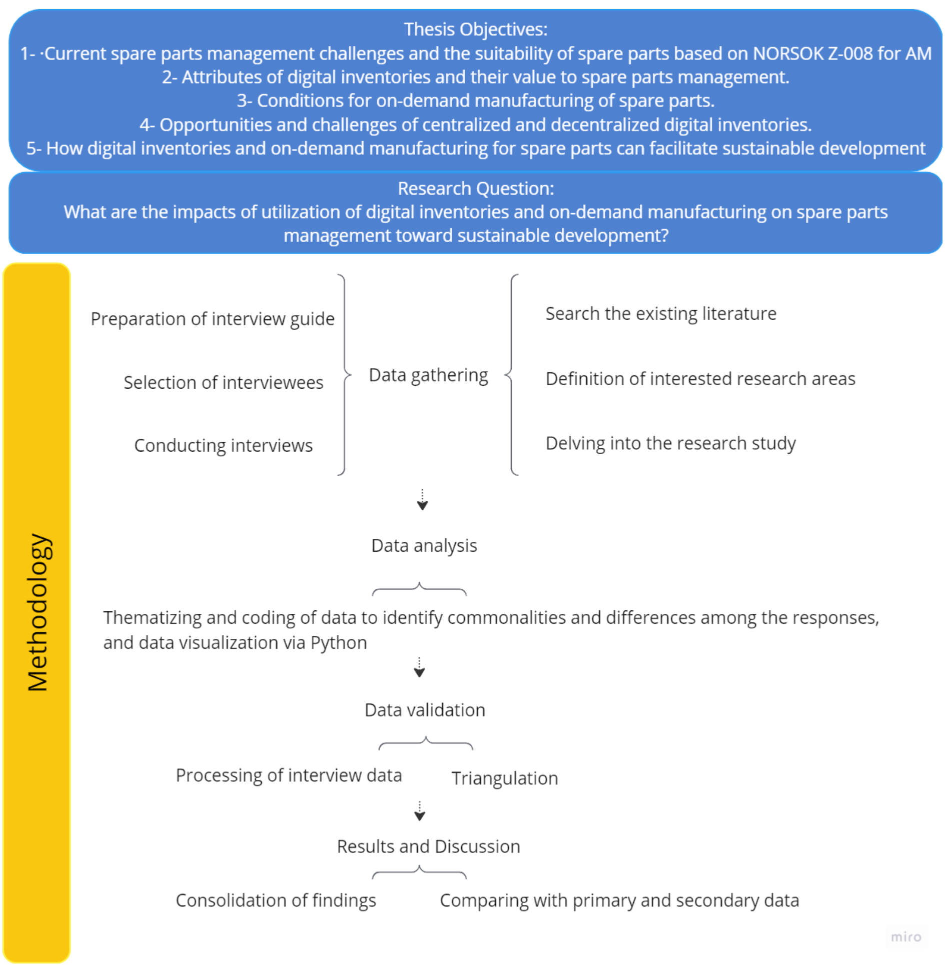

Figure 2-Methodology design and approach

2-2 Data Collection Methods

The data sources for this thesis include academic literature, professional interviews, and online resources, with semi-structured interviews serving as the primary data collection method. The interview guide included both open-ended questions, which allowed for in-depth qualitative insights, and closed-ended questions, which facilitated quantitative analysis.

A thorough approach was adopted for the literature review to establish a theoretical foundation, starting from the principles of asset and inventory management, with a particular emphasis on spare parts. This review progressed into an exploration of additive manufacturing technologies and their applications, followed by an examination of digital business models.

Special attention was given to digital platforms, analyzing their governance structures and attributes. This facilitated a discussion on the industrial identity of digital inventory platforms, particularly how they are enabled by AM technologies and their role in fostering on-demand manufacturing. Subsequently, the discourse extended to sustainable business practices, focusing on how AM and DI technologies can influence the sustainability of spare parts management. This review also considered the emergence of new technologies that can complement AM technology and identifying how they could further influence sustainable outcomes.

The academic literature used in the thesis was found and collected from Oria, Google Scholar, and Scopus. Considering the novelty of digital inventory platforms and technological advancements in the AM field that enables the industry to evaluate the possibilities of large-scale utilization of AM, and according to the thesis objectives, a broad range of topics were searched, identified, categorized, and thoroughly studied and used further to guide the preparation of interview questions.

Furthermore, the interview questions which were shaped based on literature review, were also developed continuously as a result of consultation of the author with experts in the AM and DI field, and academic advisors to ensure the interview questions' direction and coverage are aligned with the thesis objectives and, thus, ensure internal validity of the used methodology approach.

The chosen interview approach for this study project is a semi-structured interview as the application of Digital inventories and digital spare parts is fairly new and requires in-depth information for research. Semi-structured interviews leverage prepared topics for directing dialogue, while also giving participants the opportunity to uncover novel ideas, so enhancing the research approach. This style is particularly useful in exploratory studies when there is little information available. It effectively balances organized queries with the ability to dig in further, so improving data gathering through verbal communication to achieve specific research objectives. (Fox, 2006)

It was decided to contact people from relevant companies working in the field of AM and/or DI and the total number of interviews reached to 15, which include interview with representatives of different stakeholders, like operators, an OEM, AM suppliers, a Digital inventory platform, standardization company and other service providers in the field of AM.

2-3 Data Analysis and Validation

The collected data, including interview transcripts and literature review findings, underwent a rigorous process of analysis. The qualitative data were analyzed using thematic analysis, identifying common themes, patterns, and insights related to the thesis objectives.

Qualitative data from interviews is analyzed using thematic analysis. This involves coding data extracts and identifying patterns or themes related to the deployment and effects of digital inventories and on-demand manufacturing. This analytical approach helps directly connect emergent themes with the theoretical insights derived from the literature, providing a nuanced understanding of the research problem. Two software, Excel and NVivo, licensed by the University of Stavanger and accessed via student account, were used for thematic analysis.

For the quantitative analysis, responses to close-ended questions were quantified and analyzed. Python (version 3.11) was used to create visualizations to effectively reflect the respondents' opinions about a particular subject.

To provide further clarity on the quantitative analysis process, an example of a Python code used for generating these visualizations, is included in Appendices. This example demonstrates the specific steps taken to process the data and create the visual representations. (relatively similar to all bar charts)

This thesis uses Triangulation to enhance the study's credibility and validate findings. (Nightingale, 2020) described the purposes of triangulation as,

1- To enhance validity,

2- to create a more in-depth picture of a research problem, and

3- to interrogate different ways of understanding a research problem

The process of triangulation will be used by comparing the data gathered from interviews with the literature review, and consultation with AM experts to validate the findings. This approach ensures comprehensive understanding and strong validation of data across various sources.

In the discussion chapter, information obtained from the interviews compared against findings in relevant academic literature and further analysis was made by consolidation of all data to provide a thorough understanding of the thesis objectives.

Ethical Considerations

Ethical guidelines were strictly followed, with clear communication of the study's purpose to interview participants and ensuring their right to withdraw without consequences. Anonymity and confidentiality is strictly maintained to protect participant privacy. All procedures approved by Sikt (Norwegian Agency for Shared Services in Education and Research) with regards to the voice recording from the participants to ensure the anonymity of their responses.

Reliability

Reliability was ensured by continuously refining the interview guide to align with thesis objectives, maintaining consistency in the interview process, and employing a uniform method for recording, transcribing, and coding data. Additionally, quantitative data were analyzed using Python, ensuring accuracy and consistency in the visualizations and statistical representations of the data.

3- Contextual Background

Norwegian oil and gas industry has been matured since the very beginning of this industry in 1960s and has been the largest industrial sector in terms of value creation for Norway's economy in 2022. (*The Government's Revenues - Norwegianpetroleum.no*, 2024).

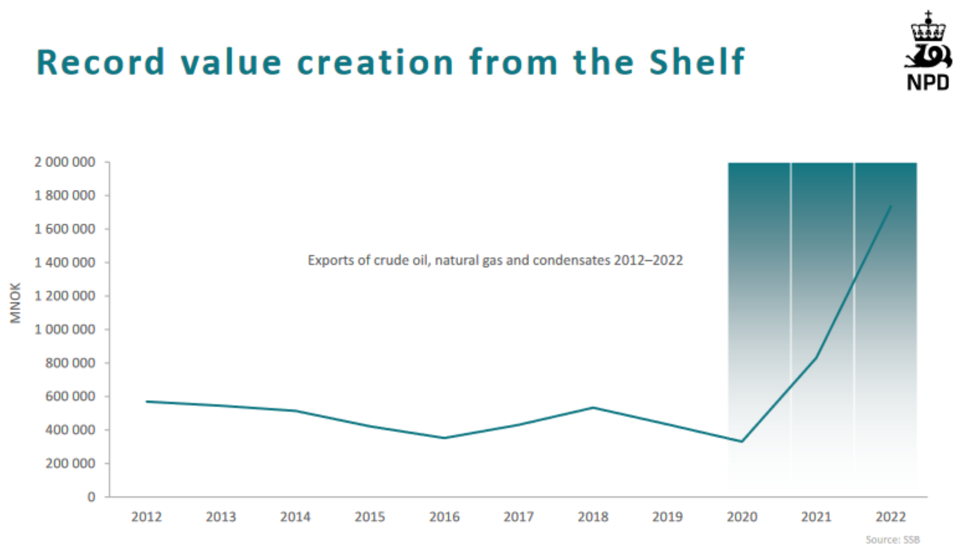

Figure 3- Value creation from the NCS (The Shelf in 2022, n.d.)

Equinor, formerly Statoil, is originally a state-owned company (still 67% state owned) established in 1972, to manage and operate Norway's petroleum resources. Equinor's continuous growth in the last decades, made the company become a major operator in the oil and gas industry that its strong presence on the Norwegian Continental Shelf culminated to 39 production license awards, in 2023, 14 of them as the operator and being a partner in 25. (*Equinor Awarded 39 New Production Licences on the Norwegian Continental Shelf*, 2024)

Based on the new development plans and licenses, the investment in this industry has been stable for the last few years, however, the investment reached to a record of 215 billion kroner in 2023 and is forecasted to peak around 244 billion kroner, which will be a 13% growth compared to last year. (Norwegian Oil and Gas Companies to Invest $23 Million in Offshore Spending for 2024, n.d.)

Thus, the industry becomes significantly dynamic, and established technological developments in the sector driven by innovative and sophisticated solutions, as a cumulative effort of thousands of companies directly or indirectly providing services.

Norwegian oil and gas industry consists of upstream, mid-stream and downstream sections for its value chain. The upstream operations in the oil and gas includes the exploration and production of crude oil and gas. These operations are highly advanced and the safety regulations to maintain the functionality of the processes and relevant equipment are strict.

Moreover, with the assistance of new technologies, remote offshore platforms can have seamless communication with control centers to enable an effective and immediate decision-making process. Furthermore, as of December 31, 2021, a wide variety of enterprises, around 36 operating in the Norwegian O&G industry. (Resource Report 2022: Norway Is a Competitive and Long-term Supplier of Oil and Gas to Europe, n.d.)

Therefore, if we take a glance at exploration activity in the oil and gas industry, this has made a considerable contribution to Norwegian society over the last two decades. The anticipated net present value of these operations, at discount rates of 7% and 4%, is NOK 1,500 billion and NOK 2,100 billion respectively. This has resulted in a net income of over NOK 3,000 billion, that is based on the high production levels recently and anticipated to be fairly continued in the coming years.

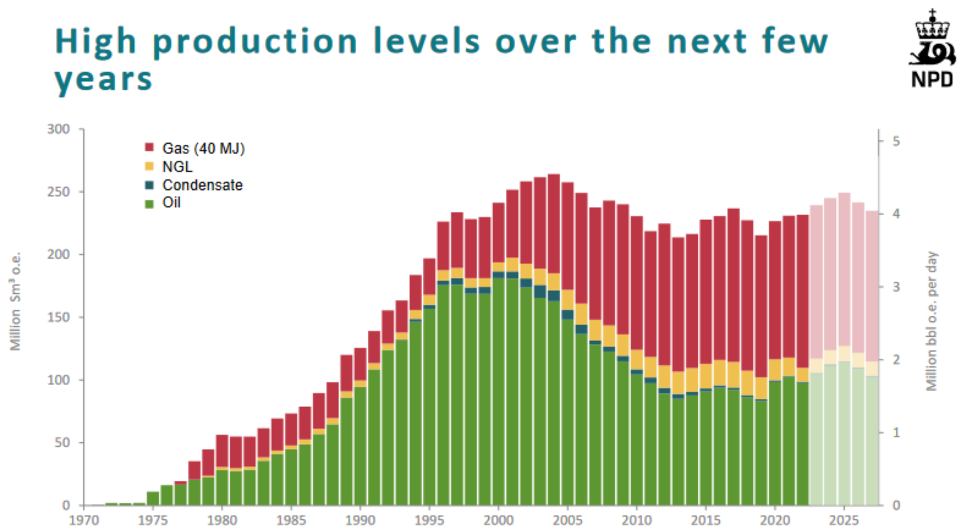

Figure 4- Production levels on the NCS (The Shelf in 2022, n.d.)

Basically, the revenue of operators and asset owners in the oil and gas industry are directly dependent on the availability of their production systems, while this availability has a critical interconnection to the availability of the spare parts to be used to maintain the functionality of the desired equipment.

Technological developments

When the oil prices declined to around $30 per barrel, in 2016, the Norwegian O&G industry was pushed to its limits and rang the bell for restructuring the oil and gas industry to diversify their investments and developments on renewable energies to become less dependent and vulnerable to external factor of oil price, as well as following the green transition in order to increase the shelf competitiveness by integrating the carbon emission reduction approach to their value creation.

Certainly, some companies started to adapt and build competence and enter the renewable energy industry sooner than others, among them Equinor and Aker are on the top. For instance, Aker Solutions has adapted its predominantly O&G-based business models to embrace change, positioning itself as a major player in offshore wind and carbon capture technologies in Norway.

Based on a recent master's thesis that studied the restructuring of the Norwegian oil and gas companies, they realized that large suppliers in the O&G industry have to contribute to the research and development of sustainable solutions and systematically adapt their business models to the green transition requirements. (Sletten, Jonasmo, & Solheim, 2021, p.56)

Furthermore, they highlight that O&G firms are engaging actively in innovation and sustainable development to maintain competitiveness which include both industry-specific advancements and ventures into renewable energy markets. However, they realized that a noted uncertainty among some companies exists on how they can effectively implement sustainable practices and what specific course of actions to take. (Sletten, Jonasmo, & Solheim, 2021, p.56)

According to this study, the primary focus of innovation in this sector is on product and process improvements, generally characterized by incremental enhancements rather than major breakthroughs. Additionally, there is a significant emphasis on service innovation, particularly in operations and maintenance, where digital technologies like Artificial Intelligence (AI), AM, and autonomous processes are increasingly applied.

Moreover, the introduction of new products and services often calls for the creation of innovative business models that are different from traditional ones. These new models are designed to accommodate the changes brought about by these innovations. (Sletten, Jonasmo, & Solheim, 2021, p.57)

For instance, Statoil's rebranding to Equinor highlights its strategic alignment with the broader energy industry rather than focusing solely on oil and gas. This rebranding is supported by robust digital strategies aimed at facilitating and accelerating the digitalization of its processes and developments.

Based on a recent study on digitalization in the oil and gas industry, the authors analyzed the digital development and strategy of Equinor and thereby highlight that "Equinor is on the right path to fully digitalized operational systems by developing its digital solutions, improving the digital skills of its employees, partnering with start-ups, and expanding its ecosystem." (Haouel & Nemeslaki, 2023)

Regarding Additive Manufacturing technology, Equinor has continuously contributed to the maturation of the technology as well as a digital supply network via AM, since 2016. They have built the AM Excellence Center and also supported several start-ups, like Fieldmade, F3nice or Korall Engineering, in which to facilitate the industrialization of AM in Norway.

Since the oil and gas industry faced a period marked by decreasing oil prices, frequent budget and schedule overruns, increasing demands for transparency about environmental impacts, and challenges in hiring skilled labor, it has become imperative to innovate and adapt. (Haouel & Nemeslaki, 2023)

Thus, investing in AM and DIs is not only a reaction to these issues, but a deliberate and calculated decision to improve operations and increase the sector's attractiveness to investors. These technologies enable the immediate production and control of replacement components, from filters to compressors, which are crucial for minimizing operational downtime and ensuring uninterrupted service. On-demand manufacturing, facilitated by AM and DI, allows for parts to be produced either on-site or near their intended location. This significantly reduces logistical challenges and costs associated with traditional production methods, while enhancing the supply chain's responsiveness and decentralization.

Furthermore, according to (Kulshrestha et al., 2024; Naghshineh et al., 2023; Y. Zhang et al., 2022), although cost considerations have historically restricted the wider use of AM in businesses within asset-intensive industries like O&G, the potential decrease in machine downtime, reducing cost of inventory for obsolete parts with the use of DI, repairing of capital spares parts, instead of replacing them, makes AM presumably a highly competitive option and a relevant sustainable strategy.

The incorporation of DI platforms can also strengthen these benefits, by reducing the uncertainties of the supply chain, and eventually, providing a clearer horizon for strategic planning of organization for further investments and developments.

4- Theoretical Background

This chapter presents a state-of-the-art literature review, offering a comprehensive overview of various aspects of digital spare parts and DI platforms. It explores the latest theories in the field of AM, relevant asset management, and sustainability, while also delving into new technologies that can be integrated with DIs and drive more sustainable outcomes for the industry. The structure of this theoretical background aims to provide a systematic, holistic, and detailed understanding of the subjects discussed, as discovered through the literature.

4-1 Asset management

Asset management approach encompasses a wide area of management subjects where an asset manager is responsible to make effective, efficient, and safe coordination between top management decisions with regards to the organizations' business objectives and strategies with technical and engineering operations. This is mainly because of the "asset" characteristics and the business environment and industrial context that the asset is operating in.

PAS 55, the Publicly Available Specification on Asset Management published by the British Standards Institute, gives the following definition of Asset Management: "Systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks, and expenditures over their lifecycles for the purpose of achieving its organizational strategic plan." And strategic plan based on PAS 55 is, "an overall long-term plan for the organization that is derived from, and embodies, its vision, mission, values, business policies, stakeholder requirements, objectives and the management of its risks." (*Asset Management*, 2008)

Asset management functions

Asset management is a response to the fast-changing, competitive, and cost-conscious business environment, and knowledge and learning are key factors to ensuring success. The organization needs to demonstrate the necessary competence in every function that is related to the asset, which includes competence in design, operation, maintenance, installation, and disposal. In other words, the organization will demonstrate competence in the whole life cycle of the asset.

In addition, there will be a clear understanding of involved risks and opportunities that exist in relation to the assets. Understanding the opportunities is essential, as it enables the organization to deploy capital where it produces the highest value. One of the most obvious characteristics is that the organization will have a clear understanding of how their assets (tangible/non-tangible or physical/non-physical) will contribute towards achieving their organizational goals and objectives.

According to ISO 55000, "asset management translates the organization's objectives into asset-related decisions, plans and activities, using a risk-based approach, to achieve the desired balance of cost, risk and performance, which can contribute tangible benefits and leverage opportunities.” (International Organization for Standardization, 2014)

Asset management is best understood as an integration framework that enables organizations to systematically achieve their explicit objectives. It coordinates various functions and activities to align with the overall business plan. Fundamentally, asset management acts as a bridge between strategic business planning and daily operational activities, promoting coherence and efficiency.

Key element of understanding asset management is to consider the asset lifecycle. According to ISO 55000, the asset lifecycle means “stages involved in the management of assets, from asset creation to asset end-of-life”. (International Organization for Standardization, 2014)

Throughout this period, asset manager aims to identify the required assets, and associated systems, how to support these assets through supporting funds or human resources, establishing asset management system and maintaining it to monitor the asset performance, and finally how and when the asset should go through the disposal or renewal process. (Hastings, 2010)

Asset management enables the organization to realize value from their assets, through providing the technical and management teams with relevant asset knowledge, in order to facilitate a coordinated activity within the organization and subsequently, maintaining and developing the business decisions to make the processes efficient and effective.

Thus, asset management is not restricted to maintenance, and encompasses a wide range of activities to improve value creation, increase asset knowledge within the organization, performance management and developing strategic plans to facilitate effective communication between technical and managerial teams to make a meaningful coordination to manage the assets efficiently and effectively, and most importantly, to bring sustainable outcomes for the organization and increase the trustworthiness of the organization for its stakeholders.

Therefore, as (Hastings, 2010) highlights, “the asset strategy must be responsive to and interact with the business strategy.” That is why and how asset management can strengthen business decisions with regards to Capital expenses (Capex) and Operational expenses (Opex). The increasing rate of globalization and digitalization derive business issues such as rapid technological evolution and increased innovation cycles in the industry, which indeed ask for innovative products and services, leading to business model developments. Clearly, this business situation requires a multifaceted decision-making process to ensure a maximum value creation process is handled while minimizing associated costs, which is exactly what asset management determines to address.

Asset management system

According to ISO 55000, to create a structured way of asset management, an asset management system is required to encapsulate stakeholders’ expectations, a strategic asset management plan, and the organization’s objectives to define a framework for relevant activities. It must integrate the interrelated elements of an organization, their functional objectives, and performance monitoring policies, addressing changes and improvements, considering risks, and accounting for the company's process capabilities and top management contributions. Figure 5, illustrates the relationship between key terms of asset management, based on ISO 55000. (International Organization for Standardization, 2014)

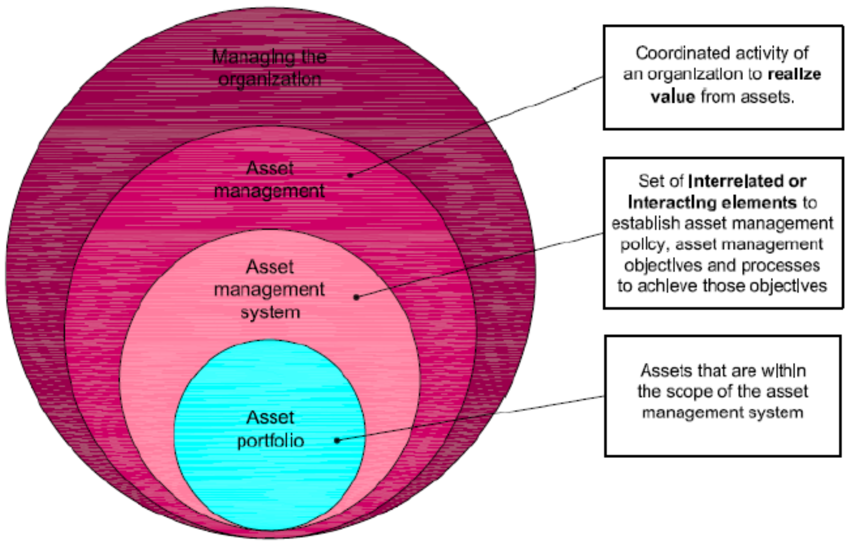

Figure 5- Relationship between key terms (International Organization for Standardization, 2014)

ISO 55000 also mentions that "asset management requires accurate asset information, but an asset management system is more than a management information system." (International Organization for Standardization, 2014)

(Hastings, 2010) also mentions that asset management systems, that can handle large amount of data gathered from different asset associated interactions within the organization, are "designed to assist the user to create and maintain documentation for the asset management function". This would provide the asset managers with interconnected data of different aspects of the assets in their respective asset lifecycles, enabling them to have informed decisions whether an asset needs repair, or it should be disposed, and a new one should be acquired.

An asset management system's analysis and integration across departments helps top management understand asset performance, risks, investment needs, and value for decision-making and strategic planning. (Chandima Ratnayake & Markeset, 2012) Moreover, an asset management system integrates technical standards, norms, rules, and best practices, improving asset management. The interconnectivity of this information with maintenance departments and procurement teams, can therefore, be aligned with the fundamental principle of asset management as coordination between activities, to derive value and balancing the short/medium/long term asset planning.

The benefits of performing asset management are substantial, and the consequences of not adopting the asset management approach could be severe. Methods that potential to increase the asset value, e.g. lower the costs and increase production effectiveness. Reduce maintenance cost and increase reliability.

Therefore, the overall benefits of adopting ISO 55000 can be understood and include as: improved financial performance, informed asset investment decisions, managed risk, improved services, and outputs, demonstrated compliance, demonstrated social responsibility, improved organizational sustainability and most important among all, improvement in processes' efficiency and effectiveness. (International Organization for Standardization, 2014)

Asset management in the O&G industry

Asset management in the O&G industry requires a holistic approach to effectively manage assets throughout their entire lifecycle. This involves streamlining asset operations and aligning related costs, risks, and performance. By providing a unified framework, asset management supports decision-making and ensures organizational alignment. Additionally, conducting stakeholder analyses is essential to identify and address the needs and expectations of both internal and external stakeholders, thereby establishing effective communication procedures as stakeholders' perceptions are crucial for future success. (Amadi-Echendu et al., 2010)

The O&G sector is structured to enhance asset performance while managing the complexities and high costs of operation. In Norway, this is particularly vital as companies strive to improve performance, reliability, and safety, while reducing costs and extending asset lifecycles. Effective asset management ensures that assets deliver optimal value to stakeholders, increasing profitability and maintaining market competitiveness.

Managing assets in the O&G industry involves navigating unique challenges, such as complex and costly infrastructures, compliance with standards, adaptability to fluctuating oil prices, investments in broader scale of renewable energy sector, and the availability of numerous critical assets in diverse locations. Strategic spare parts management is crucial to mitigate the expensive repercussions of equipment downtime, including production delays and safety risks.

Norwegian companies leverage frameworks and guidelines aligned with standards like NORSOK to ensure maintenance activities are both effective and compliant. This holistic approach not only improves operational efficiency and extends asset lifecycles but also supports the sector's drive towards enhanced environmental and safety outcomes.

4-2 Inventory management

Inventory plays a crucial role in maintaining the delivery of products and services to customers. The importance arises from this basic fact that the demand facing an organization may not always be equal to its production capacity. Thus, inventory is used to ensure the service level to address customer satisfaction, which nowadays is not a trend but a mandatory perspective if one business aims to sustain and be profitable.

Therefore, inventory management should consist of policies in accordance with the dynamic environment of the supply and demand (in general terms), to effectively plan items' supply, storage, and accessibility to ensure an adequate stock without excessive surplus. (Aro-Gordon, n.d.; Muckstadt & Sapra, 2010)

Also, (Singh & Verma, 2018) see inventory management as “the continuing process of planning, organizing and controlling inventory that aims at minimizing the investment in inventory while balancing supply and demand". As mentioned earlier, the crucial role of inventory is recognizable when we see a bigger picture of a supply chain and how inventory with its different roles, such as anticipation stock, cycle stock, safety stock, pipeline stock, and decoupling stock (Muckstadt & Sapra, 2010), in the industry, is an inevitable part of a supply chain, to ensure smooth, efficient and effective production and procurement processes.

Furthermore, (Muckstadt & Sapra, 2010) categorized the fundamental influencing factors of inventory management and its relevant policies, as follows:

- System structure: It implies the supply chain’s structure which determines the material and information flow among different stages and echelons in the value chain. The echelons are owned by different organizations which make the coordination and goal alignment complicated.
- The items: the physical attributes of the parts, the demand variability of them, the storage location for them, the obsolescence, the repairability of the parts, and finally the cost associated with parts are the key factors in proper recognition of the parts.
- Market characteristics: the uncertainty of the item’s demand rate led companies to use statistical optimization models to forecast the number of parts to comply with their specific operating context and financial strategies.
- Lead times: Basically, it means the time length between putting the order and receiving the parts. Supplier reliability and responsiveness are critical in determining the uncertainty level of the lead time.
- Cost: In inventory policy, purchasing, carrying, and stockout expenses must be managed. Asset management in oil and gas balances cost-efficiency and safety to maximize asset usefulness and profitability throughout their lives. Classifying buy volumes to avoid overstocking and reduce operating costs ensures financial and operational efficiency in inventory management.

Effective inventory management is crucial for companies to differentiate themselves and meet changing consumer expectations. To survive long-term, companies must focus on supply chain and inventory management, investing in research to reduce costs, improve quality, and decrease failure rates. (Singh & Verma, 2018)

4-3 Spare parts management

Spare parts are the parts that are supposed to be used to maintain the functionality of the relevant equipment. Therefore, in an asset intensive industry like Oil and Gas industry, the availability of the spare parts is critical as the lack of required spare parts in the right place in the right time, can have considerable negative impacts on the production rate of the company, which is understood as lost revenue, could cause a chain of hazardous events that can lead to environmental disasters or the loss of human lives, and eventually, endanger the company's reputation and business existence.

Deep Water Horizon accident can be a good example, of how lack of proper coordination can breach the safety barriers and lead to such industrial disaster that brough enormous negative financial and reputation damage for British Petroleum, as one of major oil companies in the world, in which the total costs lifted to $65 billion. (Maritime Executive, 2018) Therefore, coordination, as a critical attribute of successful asset management, shall not be underestimated.

Coordination

Coordination is a key characteristic of the spare parts management, as (Tysseland, 2009) emphasized that coordination is "the integration or linking together of different parts of an organization to accomplish a collective set of tasks." Here, it means a wide range of factors can influence the concept of coordination for spare parts management.

Spare parts management, basically, involves the strategic coordination of human resources, materials, processes, and information flows to facilitate repair and maintenance activities (Kulshrestha et al., 2024; Tysseland, 2009) which can be summarized into demand management and controlling inventories (Bhalla et al., 2021) to ensure spare parts investment optimization and system availability. (Tysseland, 2009)

The key purpose of risk assessment is to support management in rational decision making. In this research the concept of rationality is defined as a ratio between the cognitive capability of the decision maker and the complexity of the problem in question.

Clearly, the management of spare parts which requires coordination from different teams within the organization, and considering the current highly uncertain geopolitical and economic situation that impacts the global and regional markets, which could lead to the increased complexity and total costs of spare parts management, becoming a major issue for organizations operating in the O&G industry.

Spare parts management

Subsequently, critical questions for spare parts management would be, what sorts of spare parts (classification), should be ordered when (demand forecasting), and stored where and for how long (inventory management)? This will grab our attention toward the inventory of spare parts, as it is an integral value-driven asset of the industrial organizations and how it should be managed in an optimized manner. Interestingly, a comprehensive literature review by (S. Zhang et al., 2021), showed that the research trend about spare parts inventory management has experienced a steady growth, as the relevant articles raised from 5 to 148, between 2010 and 2020.

According to (Bacchetti & Saccani, 2012), they define integrated spare parts management as a cyclic process, consisting of the following elements shown below,

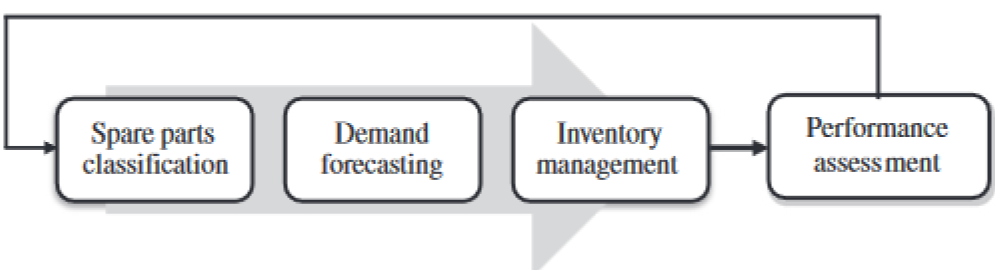

Figure 6-Elements of integrated spare parts management. (Bacchetti & Saccani, 2012)

The vast number of spare parts with their correspondent varied characteristics, makes the spare parts classification an essential part of spare parts management (Teixeira et al., 2018). This classification step will strategically ask for alignment with the demand forecasting method as well as inventory policies. To ensure this management approach is effective in responding to customers' requirements and key acceptance criteria, the performance assessment is implemented, that eventually will reassess the specifications of the spare parts against the relevant performance indicators, to adjust other steps accordingly for improvement.

Relevant studies to spare parts classification and forecasting are (Teixeira et al., 2018), (Bhalla et al., 2021) and (Hassan et al., 2012). However, the classification and forecasting methods can be highly variable and stochastic modeling is usually used. This is due to the part's manufacturing processes, materials specification, qualification requirements, value and costs, criticality, demand patterns, industrial domain, market uncertainty, and other technical and functional factors. In other words, "spare parts demand is induced by the failures and replacements of parts in use during a product's life cycle, and is often intermittent and lumpy, causing difficulties in demand forecasting." (S. Zhang et al., 2021)

According to (S. Zhang et al., 2021), spare parts are categorized into two primary types: repairable and non-repairable. Repairable parts are replaced and repaired upon failure, then returned to stock as ready-for-use units for future use, while non-repairable parts, or consumables, are discarded after use due to their inability to be repaired. The management of repairable parts is inherently more complex, involving logistics with both suppliers and repair workshops, and is influenced by factors like repair capacity and duration. In the current market, Original Equipment Manufacturers (OEMs) are increasingly motivated to offer after-sales services as a strategy to differentiate themselves competitively and drive profits, often exceeding those from product sales alone. (Muckstadt & Sapra, 2010) note that supply chain and inventory strategies must adapt differently for consumable versus repairable items to optimize efficiency and service quality.

Also, based on the contextual background, NORSOK Z-008 categorization for the spare parts is quite relevant here which are:

- Capital spare parts: – Vital to the functioning of the plant, but unlikely to suffer a fault during the lifetime of the equipment – Delivered with unacceptably long lead times from the supplier and usually very expensive – Often these spare parts are characterised by substantially lower costs if they are included with the initial order of the system package – Also called insurance spare part.
- Operational spare parts: – Spare parts required to maintain the operational and safety capabilities of the equipment during its normal operational lifetime.
- Consumables: – Item or material that is not item specific and intended for use only once (non-repairable) This known and well-established spare parts classification framework is practiced in the maintenance field throughout the industries. (Standards Norway, 2017)

According to master's thesis titled by, A Multi-Criteria Classification Framework for Spare Parts Management, the total number of spare parts for a typical offshore installation on the NCS is enormous and amounts to approximately 50k SKUs (Stock Keeping Units). (Husum, Leirvaag, & El-Thalji, 2022, p.3)

Moreover, based on their case study for three specific offshore installations, one offshore storage location, and one onshore warehouse, considering that each production facility also holds its own spare parts inventories, they estimated the proportion of each category and correspondent value of them, as follows:

Spare part type	Proportion of Total SKUs	Value contribution to Total	Notes
Capital spare parts	About 0.50 %	Substantial 35-40%	Despite their small quantity, they have ahigh unit cost contributing significantly to total value
Operational spare parts	Approximately 50%	About 45%	These are essential for daily operations and form the bulk of spare parts inventory
Consumable spare parts	Around 6%	About 0.40%	These are low-cost items used frequently and disposed of, accounting for a minimal part of the total value
Blank (unspecified)	Approximately 40%	Not specified	Includes items not yet classified or evaluated, possibly new or undergoing changes

Table 1- Spare parts categories and correspondent value based on NORSOK Z-088 (Husum, Leirvaag, & El-Thalji, 2022, p.3)

This particularly means that only a few numbers of capital spare parts possess more value than thousands of consumables, which require attention from asset manager to appropriately plan to minimize costs and maintain the availability of the operating systems.

Preparing a roadmap for optimizing spare parts requires navigating complexities across both macro (supply chain and manufacturing methods) and micro (part failure rates) levels, presenting unique challenges. In the Norwegian oil and gas sector, practitioners are particularly challenged by issues such as part obsolescence, logistical difficulties related to Norway's extensive coastline and remote offshore locations, and the delays from long lead times and supplier deliveries.

Challenges

Unlike final products, which are stocked for direct customer supply, availability of spare parts ensures a reliable operational condition, resulting in distinct demand patterns and higher obsolescence risks when products are discontinued. Consequently, strategies effective for final products often prove sub-optimal for spare parts. Moreover, management of repairable parts has been mentioned in the literature as more complex due to the need for additional repair resources (S. Zhang et al., 2021).

Among spare parts challenges that have been mentioned earlier and furthermore in the literature, here a brief focus on lead time, transportation and obsolescence is relevant to this study. The lead time, which refers to the duration between placing an order and receiving it, has a considerable impact on the dynamics of the supply chain. Implementing inventory solutions, such as emergency replenishment, can effectively decrease lead times but at a greater expense. Lead times for nonrepairable spare parts typically include the time required for delivery and, if relevant, the duration of any repairs.(S. Zhang et al., 2021)

Transportation presents a substantial risk of interruption in supply chains, especially when delivering spare parts to distant offshore locations in the Arctic or other facilities operating under harsh environments. (Muckstadt & Sapra, 2010) The level of risk is determined by factors such as the configuration of the supply chain, the number of echelons in the chain, and the specific locations where finished items are stored before being delivered. Amidst the COVID-19 epidemic, occurrences like border closures and the geopolitical event of the Suez Canal blockade demonstrated how transportation disruptions might occur, resulting in negative effects on supply networks, particularly those crucial equipment or raw material to the Norwegian oil and gas sector.

Spare parts are typically stocked to mitigate the high costs and safety risks of equipment downtime, particularly when parts are hard to source quickly, from an OEM on short notice. Inventory management aim to strategically set the inventory levels to balance the risks of downtime and obsolescence against holding costs. (Kennedy et al., 2002)

Moreover, obsolescence has become a major challenge for operators on the NCS. An interesting study by (Mellal, 2020) about obsolescence, described it as an act of becoming outdated. By adopting economics' perception into obsolescence, (Mellal, 2020) adds, "a productive asset may become outdated, and thus lose its utility, simply because of technical developments or fashion, even if the item is in its perfect operational state." While this interpretation is also quite relevant to industrial perception, the obsolescence can therefore be understood as, the side effect of technological advancements when a particular asset or equipment is no longer fit for the current demand or even the product itself is no longer manufactured.(Mellal, 2020)

In addition, (Mellal, 2020) suggests industrial systems have to prepare a cyclic and real time monitoring system to control over their assets, to prevent the consequences of obsolescence such as, unexpected production stoppages, lowering efficiency in renewable energy production plants, embargo, outdated components during the design of a system, and increasing waste.

4-4 Additive manufacturing

Utilization of additive manufacturing is not new in the industry, but it has been used mainly for rapid prototyping which is now well commercially established. (Mellor et al., 2014) Since the late 1980s, multiple businesses have been working on a manufacturing approach that entails constructing a component layer by layer in the desired shape, rather than removing material from a solid block, which as known as subtractive manufacturing. (Meier, 2020)

This understanding is aligned with the standard definition of AM established by ASTM, as AM is “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2012).

AM encompasses a variety of production processes that transform a digital drawing file, a three-dimensional computer-aided design (3D CAD) file, into a tangible component, (Hämäläinen & Ojala, 2017) which it is achieved through the sequential layering of materials. The 3D file format is STL which contains the surface geometry of the design component which is furthermore used by slicing software to generate the printing layers. (Gibson et al., 2010; Meier, 2020)

As mentioned earlier, the use of AM, also known as 3D printing, was particularly about Rapid Prototyping (RP), which is a quick way to demonstrate the functionality of a basic design and a pre-step for further developments to make the final product being available to be introduced to the market. This approach has changed since the manufacturers using RP observe the evolvement of AM machines and their applications, and thus, the quality of outputs were comparable to final product quality. (Gibson et al., 2010) Therefore, Rapid Manufacturing (RM) as “the production of end-use parts from additive manufacturing systems” (Hague * et al., 2004) has emerged and it is implemented in the industry which naturally has accelerated the product development cycles.

The annual global report by Wohlers Associates notes an increase in end-use applications of additive manufacturing, detailing that the proportion of functionally utilized parts rose from 28.1% in 2012 to 33.8% in 2016. (Wohlers, 2013, 2017)

As (Gibson et al., 2010) mentioned, most AM processes involve these eight processes:
Step 1: CAD
Step 2: Conversion to STL
Step 3: Transfer to AM Machine and STL File
Step 4: Machine Setup
Step 5: Build
Step 6: Removal
Step 7: Postprocessing
Step 8: Application

Vat photopolymerization, powder bed fusion, and material extrusion are among the most widely utilized AM technologies. Other available technologies include sheet lamination, directed energy deposition, material jetting, and binder jetting. These technologies have the capability to process a wide range of metals, ceramics, composite materials, and polymers. (Despeisse et al., 2017)

AM has a great potential to improve the production processes and enhance design properties of components and its benefits encompasses the various stages of the part life cycle. Some of these benefits as (Holmström et al., 2010) mentioned are:

- No tooling is needed, significantly reducing production ramp up time and expense
- Small production batches are feasible and economical
- Possibility to quickly change design
- Allows product to be optimized for function (for example optimized cooling channels)
- Allows economical custom products (batch of one)
- Possibility to reduce waste
- Potential for simpler supply chains; shorter lead times, lower inventories
- Design customization

Additive manufacturing has the potential to be a reliable solution for spare parts management as well, based on its short set-up times and no need for tooling, it can reduce the risk of capital obsolescence allocated for spares in the inventory and shorter lead time and delivery times, by providing on-demand manufacturing of spare parts. The spare parts on-demand manufacturing also means that it can increase the accuracy of replenishment forecasts which is directly relevant to maintaining production systems' uptime. (Muckstadt & Sapra, 2010; Peron & Sgarbossa, 2021)

This on-demand manufacturing capability is related to the intrinsic feature of AM that it produces complex products according to the digital file (CAD file). Therefore, the term "digital spare parts" have been naturally developed in this domain, which refers to the fact that manufacturing becomes digitalized as the spare part design is digitally available, and it can be received by AM machine, and make the physical part. (Chekurov et al., 2018)

(Peron & Sgarbossa, 2021), in their literature review, mentioned that high cost per product and unreliability of parts, made by AM technique, are the main barriers for further implementation. Similarly,(Knofius et al., 2021), compared quantitatively the AM and Conventional manufacturing (CM) technologies for spare parts production and discussed the different cost attributes of AM production and the immaturity of the technology, suggested that the probable scenario is that AM technology will complement CM for spare parts, rather than replacing them.

However, considering the impacts of AM on supply chain which is extensively discussed by, (Verboeket & Krikke, 2019) ,(Meier, 2020), and (Hämäläinen & Ojala, 2017), the subsequent, beneficial and proactive strategic approach for organizations is to identify the strategic and technological requirements for further enhance their capabilities and competence, to maintain their competitive advantage. The relevant steps could be to improve and configure their digital infrastructure, ICT system's capabilities, developing competencies internally and finding reliable partners. (Chekurov et al., 2018)

4-5 Digital business models

In today's information society, successful implementation of digital businesses has become more challenging as the technology is rapidly evolving and businesses providing new products and services with higher performance and cost efficiency, are challenging the traditional business models in all industries.

Technological development dynamics have significantly changed the global and regional business ecosystems, for instance, electric cars developed by Tesla, Blockchain technologies, text-based Artificial Intelligence like the introduction of ChatGPT, or Cabinless rigs based on ICT capabilities and Virtual Reality developed by National Oilwell Varco (NOV). (NOV, 2023)

In fact, it means that even giant operators in the O&G industry that are usually called as being not agile, are embracing new technologies actively as they realized that being satisfied with their current technological achievements is not enough and they need to continuously follow up the changes in the technological domains to adapt their processes and maintain their market position.

Thus, the emergence of new digital business models is real, and these models are basically centered on the data processes to create value and feed further investments, development cycles and socio-technical innovations.

Based on literature review conducted by (Wirtz, 2021), there is heterogeneity in the definition of the term "digital business" and can be interchangeably used by e-business and e-commerce. In general, the digital business definition can be adjusted based on the context and its applications, while the essence of it can be concluded as:

"Digital business is the initiation as well as the partial or full support, transaction, and maintenance of service exchange processes between economic partners through information technology (electronic networks)." (Wirtz, 2021)

The key element in this definition is how "service exchange processes" can be utilized in the industry among different parties that are working in different segments. Service exchange processes are processes that are meant to transfer the tangible and intangible goods and services, essentially the electronic data, through the physical and mobile connections in the electronic network. (Wirtz, 2021)

For example, in the B2B (Business to Business) domain, the service exchange between companies take place where each company can become either the buyer or seller, indicating that dynamic business environment along with integration of suppliers and customers can be formed. Online shops and B2B marketplaces are the instances of how the service exchange processes could be practical and increase the accessibility and efficiency of the work processes. (Wirtz, 2021)

New industrial realities define new customer needs that ask for adjustments in traditional business models to satisfy them, where technological advancements are integral part of this new business model design process. (Teece, 2010)

There is a rich literature about business models, while there are various definitions of business models discussed relative to certain industries, while others tried to give a generic definition of this subject.

Basically, a business model serves as a guide for a firm on how to deliver value to customers in specific market segments. It outlines strategies to do so cost-effectively, addressing customer needs in ways that encourage them to make purchases. Ultimately, it aims to secure "sustainable" profits throughout a company's entire value chain.

Therefore, (Teece, 2010) highlights that "all businesses, either explicitly or implicitly employ a particular business model. The essence of a business model is that it crystallizes customer needs and ability to pay, defines the manner by which the business enterprise responds to and delivers value to customers, entices customers to pay for value, and converts those payments to profit through the proper design and operation of the various elements of the value chain."

At the heart of designing for developing business models, gaining competitive advantage lies. An integral characteristic of a business model is to analyze the internal and external factors regarding to the digital business in order to identify and develop the current processes to increase value creation, for itself and its customers. Consequently, to consider the long-term success of digital businesses, the core assets and core competencies of them, are the main strategic resources and of great importance. (Wirtz, 2021)

Core assets implies all tangible and intangible assets which specialize the company's activities and competitiveness, that subsequently define the company's value creation process. Core competence implies that competencies are essential for enabling coordinated actions within an organization to leverage assets effectively and efficiently, creating value and delivering services that meet market demand. (Wirtz, 2021)

According to (Wirtz, 2021), "strategy determines the fundamental positioning of the company in the market and shapes the resource base and use." Furthermore, an integrative approach that simultaneously can appreciate the asset and competencies aspects of the organization, is required for robust strategic realignment of organization when adapting to digital business models. This realignment is required due to the technological development dynamics and its effect on shortening the innovation cycles as well as updating the society and customer expectations and acceptance criteria.

Moreover, a recent development in theoretical framework of business models established by (Ojala, 2016), considers a wider industrial context and the entire ecosystem, while incorporating the change as an inherent feature of their framework. Ojala's proposed business model framework includes four components: The product/service, network of value (direct or indirect collaboration with stakeholders), value delivery (based on the product/service), revenue model (revenue generation and distribution among the relevant stakeholders in the network).

More interestingly, digital technologies like cloud computing or contribution of digitalized manufacturing by AM, enables a new series of start-ups either with capital (to purchase AM machines) or without intensive capital. This is firstly because of their agility, based on their processes and interfaces with stakeholders that are not complicated and complex as large organizations. This agility enabled them to have iterative improvement cycles based on feedback from the digital market, which they can get access to in a fraction of time compared to traditional business models. (Sewpersadh, 2023)

Additionally, modern digital business models are heavily centered around customer experience and personalization, which startups can more readily experiment with and implement. Using digital platforms, startups can engage directly with their customers, iterate their products based on real-time feedback, and personalize their offerings to enhance customer satisfaction. (Sewpersadh, 2023)

It suggests that start-ups whether they are merely developing software or hardware solutions, they are positioned well in local value creation, by accessing to global market, and by implementing diverse technological opportunities pushing the supply chain into a decentralized digital supply network.

Therefore, digital industrial platforms can bring this opportunity for integrating processes to create a co-value creation enabled ecosystem between geographically dispersed businesses, from different industrial sectors, to empower the market stability and customer satisfaction and loyalty, which increase the efficiency of processes and improve the supply chain’s traceability and accountability.

4-6 Digital platforms

Digital platforms basically serve as a technology-enabled business model that generates value by facilitating multi-dimensional connections between heterogenous parties, typically in forms of B2B or B2C interactions.

The study of digital platforms is intricate because of their decentralized nature and profound interconnections with institutions, markets, and technologies. As these platforms rapidly expand and evolve, introducing complex structures and entering various industries, they present new and complex research challenges. (De Reuver et al., 2018)

This has resulted in various definitions of digital platforms, as the domain industries and the applications of these platform are very different, from social media platforms like Facebook, mobile operating systems like Android and IOS, to payment platforms like PayPal and Apple

Pay. The common characteristics of these platforms can be concluded that they mediate different groups of users and suppliers in a digital environment to create value, which is denoted as multi-side platforms. (De Reuver et al., 2018)

(Chen et al., 2021) described a digital platform as: “digital systems that facilitate communications, interactions, and innovations to support economic transactions and social activities.” With a wider strategic view, “a digital platform can be described as a sociotechnical system, integrating both the technical components like software and hardware, along with the corresponding organizational processes and standards”. (Tilson et al., 2012)

Therefore, functionality and design architecture of these platforms are tied to their domain applications and information system infrastructure. In the industrial context, the usage and participation in digital platforms is more complex due to the B2B structure of the interactions and the strategic and financial intricacies of each organizations has, to maintain their competitive advantage through implementing security measures for their information usage and storage. Thus, the coexistence of different organizations’ strategies with the digital platform policies has been challenging. (Pauli et al., 2021)

Furthermore, Digital industrial platforms are rising as a result of progress in cloud computing, edge computing, big data analytics, and artificial intelligence. These breakthroughs together propel the expansion of the Industrial Internet of Things (IoT). Additionally, suppliers of Platform- or Infrastructure-as-a-Service (PaaS/IaaS), such as Amazon Web Services (AWS) and Microsoft Azure, are entering the manufacturing industry by offering customized platforms or supporting the essential infrastructure, services, and technologies. (Pauli et al., 2021)

(Pauli et al., 2021) highlights that two building blocks of a platform which are also true for the digital industrial platforms are, firstly, they facilitate the collection and analysis of data from a wide range of industrial assets and equipment, including individual tools, machines, vehicles, warehouses, and factories. Secondly, numerous platforms provide marketplaces that streamline the distribution and utilization of newly created applications to a broad base of industrial customers. As such, digital industrial platforms have emerged as a crucial element of Industry 4.0, exerting a substantial impact on the manufacturing industry in recent times.

Thus, it is concluded that regarding the technological foundation and market intermediary aspects of these platform, the aim of digital industrial platforms is to “collect and integrate industrial asset data centrally and leverage this data for the creation of smart applications and services with the help of complementors.” (Pauli et al., 2021)

Governance

Research on ways to govern digital platforms has been continuing, as (De Reuver et al., 2018) emphasizes the need of achieving a balance between various interests when developing the governance of digital platforms.

According to (Chen et al., 2021), an effective governance structure should leverage two parameters simultaneously including individual incentives and local information. A digital platform that can address these factors can achieve desirable participation rate among the suppliers and customers and can therefore, build up an industrial ecosystem to promote and maintain sustainable interconnectivity among actors to fulfill their needs with respect to their interests.

On one hand, it is a vital aspect of governance structure that both digital platform owners and participants identify their roles, goals and interests within the platform, to leverage the individual incentives.

On the other hand, a digital platform must ensure that all available information is leveraged properly within the system in order to facilitate the effectiveness and robustness of governance structure processes and outcomes. (Chen et al., 2021)

Subsequently, a question would arise that what level of decentralization can ensure a robust fit-to-purpose governance structure? The governance decentralization level is of great importance as it can vary from fully decentralized to fully centralized digital platforms.

Drawing conclusion from the literature, in fact, the functionality of centralized and decentralized formations is highly dependent on two key elements, first, in which industry the platform is operating and second, what type of business interaction the platform is supposed to address, most probably between B2B and B2C.

This is important, as (Hasler et al., 2022) particularly discussed that the different characteristics of B2B and B2C digital platforms is rooted basically within the interactive nature of complex organizational decision making processes, marketing strategies, and sale cycles which are not highly relevant for B2C domain where the customers are individuals.

Furthermore, (Hasler et al., 2022), compares the operational design of B2B and B2C platforms as:

“While the key transaction in B2C is a human transaction that is facilitated via an orchestrating platform, transactions in B2B are data exchanges from one device to another. When shared openly or at the boundary of the platform ecosystem, data and knowledge can be used for the co-creation of joined smart services.”

In a centralized governance structure, the platform owners have sufficient control over processes and outcomes, which might not be favorable for various stakeholders and platform participants.

On the other hand, a single location or system that possesses the control, often leading to more straightforward management and decision-making processes and can be useful for Data Consolidation as possibly it can Offer a unified view of information, facilitating easier analysis and forecasting. (Chen et al., 2021)

As mentioned earlier, the participants are businesses and organizations (B2B) that their presence in the digital platform means that they are providing or promoting their products and services in the form of data. Subsequently, their data privacy and control are in the hands of centralized platform owners.

Thus, participants believe that in a case of any security breach for a centralized platform, they are prone to serious vulnerability concerns as their data are directly or indirectly define their competitive advantage in the market, which can affect their market position and reputation significantly, and even be a threat for their business existence. (Chen et al., 2021)

This situation can be understood as risk concentration which is the attribute of centralized platforms as opposed to distributed risk attribute of decentralized platforms.

In a centralized digital platform, the occurrence of heavy governance mechanism is a probability that could profoundly change the core business model of the digital platform as it can negatively affect the co-value creation by the ecosystem policies, designed by platform owners. (Hasler et al., 2022)

In the decentralized governance structure, the platform participation power is enhanced as the stakeholders have more effective communication channels with platform owners and other stakeholders. This can result in higher rate of engagement, influence and control over the platform processes and toward co-value creation and innovative solutions within the digital ecosystem. (Chen et al., 2021)

Practically, if the power balance check is not implemented properly in centralized governance structure, then it can be easily challenged by open market principles such as flexibility and rapid adaptation to market needs. However, this formation can be utilized when the technology and its relevant market is not mature enough to boost the industrialization and basic operations and reduce the ambiguity and uncertainty to a certain point to gain the trust of industrial stakeholders in participating and operating in the ecosystem.

The name of the game after all, is the performance of the digital platform, which can be achieved if the platform is developed sufficiently by the participation of stakeholders, and how the platform strategy toward the network effects is and what are the implemented mechanisms to manage and solve the conflicts of interests, the decision making processes authority and continuously optimize the co-value creation and cooperation among actors responsively. (Chen et al., 2021)

Leadership is also another factor, that if it is effectively addressed, can bring significant value to the digital platforms and promote and encourage trust in the platform, which can subsequently increase the participation rate.

Drawing insights from (Chen et al., 2021), the opportunities and challenges of centralized and decentralized digital platforms is summarized into the following table:

	Centralized	*Decentralized*
Opportunities	• Efficient decision-making and execution. • Strong leadership • Potential for further technological development	• Increased transparency and trust through decentralized governance. • Enhanced security and resilience through distributed control. • Greater community participation and inclusivity.
Challenges	• Lack of transparency and trust. • Vulnerability to single points of failure and security risks. • Limited community participation and potential for bias in decision-making.	• Slower decision-making process • Lack of effective leadership • Potential for governance difficulties in achieving consensus and aligning diverse interests.

Table 2- Comparison between centralized and decentralized governance structures

4-7 The concept of Digital inventory platforms

Digital inventories

(Tubis & Rohman, 2023) exclusively worked on a systematic literature review of "intelligent warehouse in Industry 4.0". They argued that functions and design of smart warehouses are aligned with Industry 4.0 principles and could address the digitalization process of organization through providing modular services which are interoperable, more decentralized and enable real time monitoring of assets and increasing the flexibility of the solutions as well as their reconfigurability. (Tubis & Rohman, 2023)

However, during their discussion of several attributes of Industry 4.0 and its relevant technologies, they did not mention Additive manufacturing nor the relation between AM and warehouse, which subsequently they did not encounter the term "digital inventory" in their research as well.

(Kunovjanek et al., 2022) mentions the "digital warehouse" in the context of AM utilization, which can be useful to prevent stock-out risks, obsolescence, and lead time.

Furthermore, (Ballardini et al., 2018), clearly discussed about "digital inventories" with regards to digital spare parts and additive manufacturing. They further gave an example from Boeing, where they established a system, a virtual inventory of parts, acting as a data repository or database for technical information of spare parts management.

Here, a brief description of data repositories is provided to clarify the functionality of the digital inventory as a data repository, without delving into the technical, IT-related details of it, because it clearly calls for another thorough research in itself, and, therefore, it is not within the scope of this thesis.

Data repository is a general term that typically is used in the context of data storage, and it refers to the collected, organized, and isolated data to enable analytics for business operations. One type of a data repository is database, which can be small or large database infrastructure that use the collected data for input, storage, search, retrieval, and modification of data for further querying processing that enable the analytics and subsequently management of the information. (Ahuja, n.d.)

With the function of querying, for instance, a database can identify the obsolete spare parts in a physical inventory that has not been used for two or more years. Additionally, several factors can shape the database mechanisms such as the data type, data structure, querying processes, latency requirements, transaction speeds, and purpose of data usage. (Ahuja, n.d.)

Consequently, one must notice the difference between the data repository owned by an OEM to store its product design files, and the digital inventory platform that is a scaled-up data repository to facilitate the procurement processes of digital spare parts, mainly between OEMs, AM suppliers, and end users, acting as a multi-sided market.

The basic reason behind having digital inventory platforms is that the OEMs may or may not being interested or even able – mainly based on their strategy or cybersecurity capabilities – to be in direct contact with different customers, whether it is a loyal customer or a new customer. Thus, they would prefer an intermediary platform that could manage the relevant "service exchange processes" to ensure the compliance, security, and reliability of the transactions.

Throughout the study by (Ballardini et al., 2018), they realized a digitization trend of the existing inventories to provide flexible and scalable services regarding spare parts, via e-commerce (digital) platforms and found out that several OEMs (Original Equipment manufacturers) have already started to develop strategies regarding the development of digital inventories.

(Ballardini et al., 2018) identified several strategic advantages of developing digital inventories:

- Improving the availability of original spare parts to suppliers and customers by using a digital platform as a single contact point.
- Facilitating the process of finding product information, including products' CAD files and other technical and non-technical specifications.
- Improving the pricing and purchasing process through an easy-to-use internet platform; and
- Centralizing digital data on spare parts to provide a more comprehensive view of the company's spare part business.

Digital inventory platforms

Based on what has been discussed earlier, it becomes clearly reasonable that digital inventory platforms can offer a bright horizon of integrating different supply chain structures related to spare parts. According to the characteristics of digital platforms, digital inventory platforms can provide "localized information" for OEMs, 3D manufacturers (suppliers), end users, regarding the qualification for spare parts, all relevant physical attributes of a particular part, the procurement details of estimated lead time, unit price, etc.

This integrated presentation of spare parts' information on an online platform, improves the visibility in the supply chain which according to (Ivanov et al., 2022), will result in higher levels of efficiency, sustainability and trust.

Also, based on the governance formation of digital inventory platforms, they "incentivize the participation" of different OEMs with different range of products, small fabricators as well as large 3D manufacturing facilities, regulatory bodies, enabling a digital market with a number of operators whose demand for spare parts is large, when we review the number of current production licenses on the NCS, and their need to ensure spare part availability to prevent high financial impact of production loss or breakdown costs.

Thus, digital inventory platform are relevant useful digital tools for asset intensive industries like O&G industry, to increase operations' efficiency, total productiveness, minimizing all costs associated with their physical inventory while ensuring availability of certain type of spare parts to increase the planning accuracy of maintenance activities, fruitful involvement in the emerging digital supply network, coping with technological advancements, and nevertheless, participating in a step-change transition toward a result and value-driven sustainable business model, contributing to a more resilient and sustainable supply chain on the NCS.

Moreover, drawing from the insights provided by (Pauli et al., 2021), the key attributes of industrial digital platforms which are also relevant for digital inventory platforms, can be systematically interpreted as follows:

Attribute	Description
Multi-sided Nature	These platforms serve as dynamic hubs connecting different user groups such as buyers, sellers, service providers, and consumers. This fosters collaboration and knowledge sharing, enhancing innovation and streamlining processes to boost productivity and efficiency in the industrial ecosystem.
Network Effects	As more participants join and interact, the platform's value and utility increases, attracting even more users. This organic growth enhances efficiency and expands market access.
Interconnectivity	Seamless connectivity between systems, devices, and applications promotes efficient interactions and data exchange, enhancing collaboration and enabling

	market penetration across geographical boundaries.
Data-driven insights	Digital platforms analyze vast amounts of data from user interactions and transactions, providing deep insights into customer behavior, market trends, and operational performance, crucial for strategic decision-making and driving business growth.

Table 3-Key attributes of Digital inventory platforms

Governance/System structure

Another relevant aspect to digital inventory platforms is the difference in their governance structure which can have various impacts on the value network and also the sustainability aspect of it. As of the author's knowledge until now, a study on particularly identifying or comparing the centralized and decentralized digital inventory platforms has not been found which primarily shaped a part of motivation of this thesis to take a further step in realizing the identity, attributes and impacts of digital inventory platforms' governance on the AM ecosystem in the Norwegian O&G industry.

Where centralized digital inventories act like a central library, a more decentralized formation of it could act as a host or a hub for varied digital inventories, even connecting centralized digital inventories in itself. The main relevant stakeholders in this network are OEMs, Digital inventory platform owners, Operators (End-users) and the suppliers (3D manufacturers). While the number of stakeholders in a digital supply network is obviously far more than these, however, within the scope of this thesis, the focus is on roles of these stakeholders only.

Where centralized digital inventory acts like a central library presenting a large number of items with different authors, the decentralized digital inventory platform act as an integrator of independent digital inventories, owned primarily by OEMs, to establish a digital network between them, suppliers, and the operators.

A relevant representation of these platforms' governance would be like this:

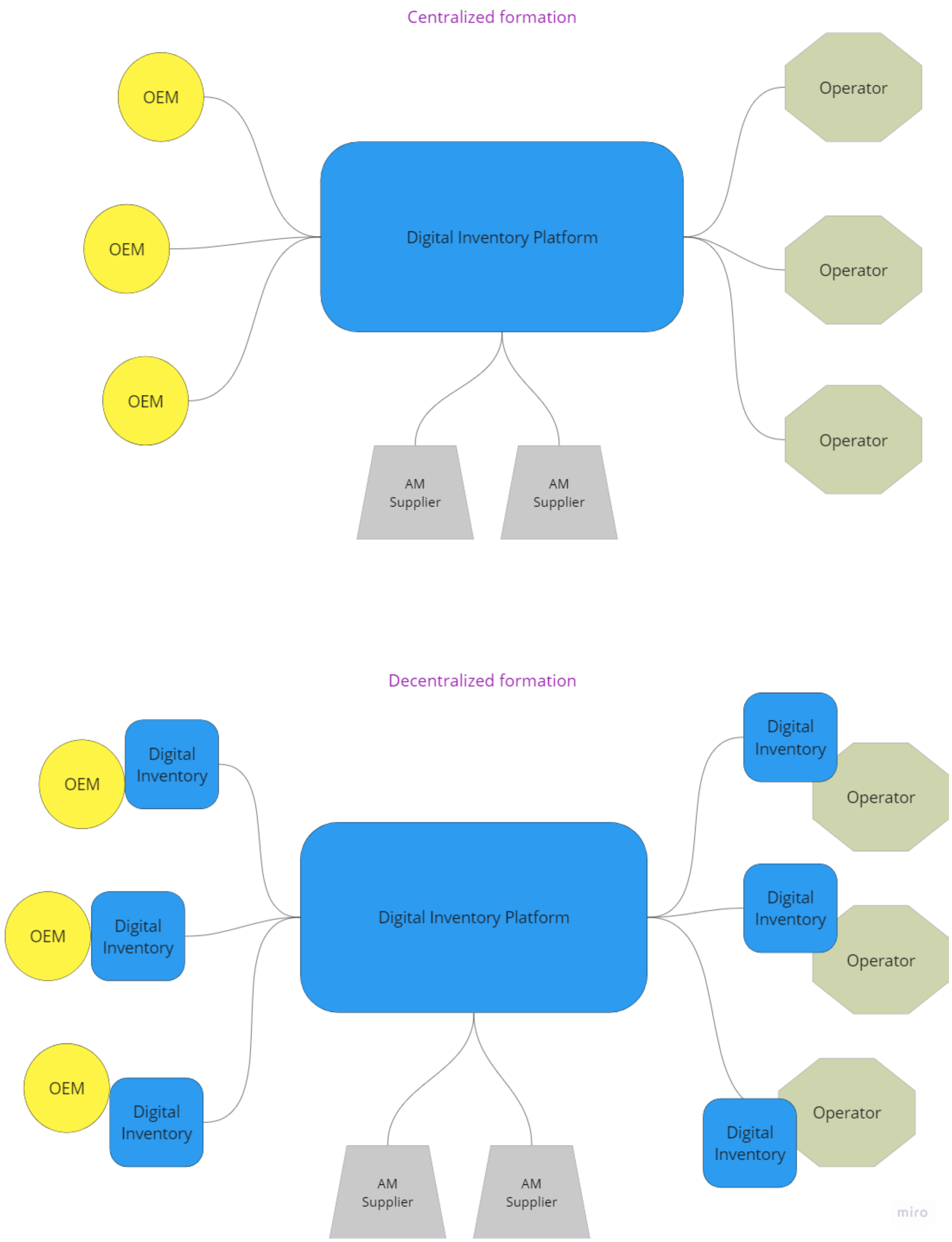

Figure 7- Centralized and decentralized formations of DIs

In the decentralized formation, relationship between stakeholders can vary according to their mutual needs and the governance of the digital inventory platform is limited to establishing a platform for a safe and secure transactions between these stakeholders, not necessarily possessing any digital spare parts.

While with the centralized formation, the processes will be more regulated by the platform owners and the flexibility of them may not be favorable for all stakeholders, as on the flip side, it requires less in-house digital infrastructure as many processes will be handled by the platform itself.

It worths to be noted that effective governance of digital platforms and as such DI platforms, based on the details mentioned by (Chen et al., 2021), in the previous section, dependent on how they leverage local information and individual incentives to satisfy platform participants' diverse interests and requirements. Subsequently, addressing these aspects is highly dependent on technological solutions, internal policies and mechanisms of platforms and it is relevant for both DI formations.

4-8 On-demand manufacturing

As (Montes & Olleros, 2020) mentions, "studies of on-demand manufacturing are scarce, limited in scope". Nonetheless, additive manufacturing, as a key element and contributor to on-demand manufacturing, is the main focus of on-demand manufacturing in the literature, while other technologies, like the use of CNC machining, can also be a source of value creation toward on-demand manufacturing.

On-demand manufacturing, as defined by (Westkämpfer, 1997), is a responsive production model that production starts only when a customer order is received, eliminating the need for large inventory stockpiling. This approach supports product customization, rapid machinery reconfiguration, and brings factories closer to markets. Furthermore, on demand manufacturing model can be increasingly empowered by implementation of AM and robotics, to an economically feasible manufacturing mode which can play an important role in enhancing the supply chain's both in terms of efficiency and responsiveness against cyclic demands, market uncertainties and capacity shortages. (Westkämpfer, 1997)

For example, although Boeing used 3D-printed parts for several years, the continuous supplier shortfalls, forced them to heavily invest in producing mixed-metal items with the collaboration of a start-up company, Digital Alloy, to manufacture required parts near to central assembly line, shortening its supply chain and accelerating production. (Cosgrove, 2018)

In order to have a comprehensive look out on what on-demand manufacturing is, relevant concepts to it in the literature can be named as mass customization, digital platforms, micro factories and just in time (JIT) production.

While on-demand manufacturing integrates mass customization, it enables individualized customer co-design, and leverages digital platforms, which result in connecting diverse groups to create and exchange value, as highlighted by (Choudary et al., 2016).

Additionally, micro factories (small fabricators) facilitate the shift from artisanal to mass production by enhancing on-demand capabilities (Montes & Olleros, 2020), while just-in-time (JIT) methods supported by additive manufacturing minimize production costs and improve geographical distribution (Ballardini et al., 2018).

The systematic coordination side by side, the technological and operational integration of AM and DI processes, would enable a robust on demand manufacturing approach to supply spare parts on demand, on time, and on site. The analysis made by (Montes & Olleros, 2020) shows that "online (digital) platforms are becoming core elements of on-demand manufacturing ecosystems across the world."

To have a seamless integration to digital platforms, on demand manufacturing platforms need to address several factors like, possessing advanced manufacturing technologies with a proper capacity management, a network of certified manufacturers, and access to a dynamic market. (Langefeld & Langefeld, 2023)

With regards to the utilization of advanced manufacturing technologies, AM is one of the core components of Industry 4.0 and facilitates the digital manufacturing and regarding its unique characteristics mentioned in section 4-4, make it an advanced technology. However, the capacity of AM machines are still limited. (Ballardini et al., 2018; Kunovjanek et al., 2022)

With regards to certified manufacturers, qualification and testing of material, process and final products' specifications to AM standards are challenging subjects for AM suppliers and the AM market. In a same vein, (Chekurov et al., 2018) mentioned that for certain applications, every single material must gain qualification approval. Moreover, (Ballardini et al., 2018) in their research, observed that "quality assurance and certification have become another barrier to the integration of AM technology into established manufacturing environments." Therefore, the next part is dedicated to analyzing the qualification process within the context of Norwegian O&G industry.

DNV and AM-related qualifications

Det Norske Veritas (DNV) is a globally leading standard company, providing various industrial solutions for maritime and oil and gas industry, established in 1864 in Oslo, Norway.

DNV, historically, has shown an effective collaboration with the industry, keeping up the pace with rapid technological advancements, to provide required standards to empower a dynamic market and facilitate safe work processes, ensuring the Norwegian industry stays competitive globally and attractive for further investments and innovations.

DNV has published different AM-related standards, as it is summarized and elaborated in the following table.

Standard ID	Description and focus	Source:
DNV-ST-B203	Focuses on the additive manufacturing of metallic parts for critical applications in the energy and maritime industries. It includes requirements for the qualification, quality management, and manufacturing processes for various AM technologies	(*DNV DNV-ST-B203*, 2022)
DNVGL-SE-0568	Service specification for qualification of AM manufacturers and facilities. It ensures that parts produced are suitable for critical applications, especially in energy and maritime sectors	(*DNV Unveils New Additive Manufacturing (3D Printing) Service Specification to Support Digital Transformation of the Energy Industry*, 2021)
DNV-CG-0197	Provides guidelines for the qualification and certification of materials and components made through AM. It integrates AM with conventional manufacturing for specific case-by-case applications	(*Standardizing Additive Manufacturing for the Energy and Maritime Industries*, n.d.)
DNV-RP-A203	Offers qualification procedures for new technologies, including AM, to structure the qualification of technologies within critical sectors like energy and maritime	(*Additive Manufacturing Enters the Maritime Mainstream*, n.d.)
DNV-RP-E402	Outlines the requirements for additive manufacturing of thermoplastics, primarily targeting maritime applications, detailing procedures for design, production, and certification	(*Additive Manufacturing Standards and Guidelines*, n.d.)

Table 4-AM-related standards established by DNV.

which has a significant impact on the connecting and directing the research about AM technology specifications to industry's demands. However, the process of certification is timely as the parts may need to be transferred from the point of production to other cities to be tested by authorized facilities and more importantly, the price for certification for the facilities and per product is quite expensive.

A key practical standard for qualification of AM parts in the Norwegian O&G industry is DNV-ST-B203, which focuses on the qualification of metallic parts made by AM.

Furthermore, based on DNV-ST-B203, “the objective of this standard is to provide an internationally acceptable framework for additive manufacturing with the aim of obtaining a consistent quality of additively manufactured metal parts and of providing predictability in the supply chain to reduce lead time and costs.” (DNV, 2021)

The standard focuses on requirements and guidance for, “the qualification of parts made by AM for the energy and maritime industries and related industries, the purchasing of AM parts, quality management by manufacturers of AM parts, the manufacturing of AM parts.” (DNV, 2021)

Additionally, based on this standard, the qualification levels that manufacturers can prequalify are:

- Facility level qualification
- Build process qualification (BPQ) per material
- Part qualification for part families

Subsequently, the standard defines three AM categories for part criticality, that the criticality levels are correlated to end user’s considerations, where AMC 3 criticality is the highest criticality. The qualification level based on this standard is as follows,

- For AMC 1 Parts:

Facility Audit + At least one BPQ = Qualified Manufacturer for AMC 1 parts

- For AMC 2 & 3 Parts:

Facility Audit + At least one BPQ + Part family qualification = Qualified Manufacturer for AMC 2 & 3 parts

A systematic reflection on these processes involve conducting a facility audit to ensure the manufacturing facility meets required standards, validating the build process through BPQ to confirm it meets specified quality and performance standards, and subsequently, verifying that a family of parts meets the necessary qualifications and performance requirements.

Licensing for digital spare parts

Another important factor as mentioned earlier is accessing to dynamic market, in which considering how new alternative business models can be implemented to promote digital spare parts and the subsequent implementation of on-demand manufacturing for them. A recently discussed solution in the literature is licensing for spare parts, to ensure the IPR protection of OEMs over their digital files, and preventing from infringement, availability of parts for the buyers and optimizing a fair economic interface between the OEMs and buyers.

For OEMs that are currently operating with traditional centralized manufacturing and sales channels for physical parts, can be motivating if they can adopt a digital mechanism to introduce a new revenue stream, becoming a licensor for digital spare parts and selling the design and right to print for buyers, and still keep their production lines, focusing on high volume production. (Y. Zhang et al., 2022)

In fact, licensing is an established method in other industries like telecommunication, however, implementation of it in the oil and gas industry for spare parts is a new approach. Licensing, generally speaking, is selling the right to use, and for AM-related context, it means using the digital spare part file, to be printed. “With the original design file, the printed parts are assumed to be identical in quality to those manufactured by the OEM.” (Y. Zhang et al., 2022)

The important criteria here is how the licensor defines the terms based on the volume of the usage, for our case, how many will be printed per digital file.

Thus, one can consider that this decision can be dynamic as well as quite complex as many factors needed to be considered, such as, spare part value and criticality, risk of imitation, industrial relationship management, reliability of digital solutions and platforms, etc.

Therefore, to simplify this complexity, the literature suggested that revenue from licensing can be gained through fixed fee, royalty fee, or mix of both. (Y. Zhang et al., 2022) A fixed fee that is paid annually or in other timeframes, allow the buyer to utilize the intellectual property (IP) for producing spare parts via 3D printing, and the royalty fee is a per-unit fee charged based on the number of parts printed using the licensed IP.

A quantitative analysis, researched by (Y. Zhang et al., 2022), over licensing optimal policy, revealed that the introduction of IP licensing brings the OEM an average of 162% increase in profit and 39% of average inventory reduction in the supply chain. Also, under an assumption of relatively low price for printed parts (p) or equal to the price of traditionally produced parts (w), (i.e. $p/w \in \{1, 1{:}5\}$) the implementation of IP licensing is huge and in 61% of the instances OEM would make use of it, and the rest would be a combination of traditional manufacturing or a hybrid use of both IP licensing and traditional manufacturing.

This in turn, makes a huge impact on supply chain configuration toward a heavy decentralized formation, with average profit improvement of 400% and the average inventory reduction of 73%. (Y. Zhang et al., 2022)

Interestingly, this result is in line with the analysis of (Holmström et al., 2010), as they discussed that between centralized and distributed production of AM parts, centralized AM is more likely to be used than distributed at the beginning stages of AM industrialization.

Furthermore, based on a quantitative analysis studied by (H. Khajavi et al., 2018) , they realized that a hub configuration in AM strategically positions AM machines near regional demand centers, balancing the advantages of centralized and decentralized production. Unlike fully centralized systems with all machines in a single location or fully decentralized setups with dispersed machines, hub configurations optimize both resource utilization and delivery efficiency.

For example, a centralized AM facility might struggle with high delivery costs and delays, while a fully decentralized system faces high initial investment and operational costs. A hub configuration mitigates these issues by requiring fewer machines and less labor than decentralized systems, achieving better production capacity utilization. It also reduces transshipment costs and delivery times compared to centralized systems, enhancing responsiveness to regional demands. (H. Khajavi et al., 2018)

4-9 Sustainability

In today's world, when organizations face escalating uncertainties and risks, change is inevitable to pursue excellence of business performance which will also present various challenges for them.

Improving the business performance of an organization is tied to a deeper understanding of several factors, like the shaping forces of the competition in global industry, the new business settings, and the fitness of business models to the future needs. (Liyanage, 2016)

The subsequent actions are dependent on how leadership in an individual organization adjust their business models to these factors, create a new balance between its resources and competencies and the business environment risks and vulnerabilities, to reform and realign their decision-making processes with the governing circumstances, to respond timely and efficiently. (Liyanage, 2016)

Thus, a mere focus on financial strength, size and scale of operations is now challenged by social forces on modern business legitimacy on how a business properly addresses corporate social responsibility or sustainability concerns. In other words, gaining commercial success in the future does not any longer solely depend on tangible and fixed assets, but is constituted of intangibles, like knowledge, cooperation, and reputation. (Liyanage, 2016)

According to (Kaplan & Norton, 1992), long-term value creation of organizations can be sacrificed for short-term performance, if they ignore the importance and proper exploitation of intangibles and reach a deep understanding of customers' and stakeholders' needs and expectations.

Clearly, this value creation fundamentally relies on current organizational processes and therefore, businesses realized that to improve their solutions, they need a new set of management practices that appreciates non-financial aspects as well, interestingly, to ensuring sustainable profitability and growth in the future.

Therefore, as mentioned earlier, corporate social responsibility which asks for attention to the societal impacts of corporate performance, and sustainability which encompasses a diverse range of economic prosperity, environmental quality, and social equity, have gained acceptance in the global business environment (Liyanage, 2016) and organizations are eager to implement sustainability-oriented strategies, to showcase the sustainable outcomes, both to public and internal stakeholders, to curate competitive advantage and foster new performance management practices to address business performance excellence.

According to UN Department of Economic and Social Affairs, the sustainable development strategy is, “that meets the needs of the present generations without compromising the ability of future generations to meet their own needs.” (*Sustainability | United Nations*, n.d.)

As a subsequent part of a deep analysis on the sustainability concept, (Liyanage, 2016) concluded that, “in general, the principal emphasis here is on the simultaneous meeting of a fourfold objective:

- social progress which recognizes the needs of everyone
- effective protection of the environment
- prudent use of natural resources
- maintenance of high and stable levels of economic growth.”

Recent studies, such as Circularity Gap report (CGR, 2022), reveals that “the world has gone from 9.1% circular in 2018 to 8.6% in 2020, annual global resource (virgin materials) use has surpassed 100 billion tons and inequalities have widened across and within countries—and it is now over 1-degree warmer than in pre-industrial times.” Also, informs that “70% of greenhouse gas emissions are linked to material handling and use, and satisfying our needs and wants with fewer materials can have radical impacts.”

A similar observation by a recent analysis made by (Cowger et al., 2024), also reveals that “every 1% increase in consumer goods companies’ plastic production is associated with a 1% increase in plastic pollution in the environment”. Then, clearly, if plastic production decreases 1%, it can decrease plastic pollution 1%, and nevertheless, this is the opportunity that we can attempt to pursue, and requires contributions from academia, industry, regulatory bodies, and the governments.

Therefore, if we take a moment and once again pay attention to “the ability of future generations to meet their own needs”, as described by UN for sustainability development strategy, the recent studies show that the consumption rate is increasingly more than the ability of what earth can naturally replenish, which asks for new strategic approach as well as immediate, coordinated and decisive actions locally and globally to effectively control the unleashed development of linear economy’s mindset and operations of extract (take)-make-waste.

Consequently, the necessity of developing sustainable businesses that pursue coordinated environmental, economic, and social activities and objectives which will address both the short- and long-term needs of stakeholders becomes clear, and asset management approach can be quite practical, addressing these issues.

The circular economy (CE), is a sustainable framework and a new paradigm, gaining momentum in industrialized and developing countries that aims to minimize waste, optimize resource use, and extend the life cycle of products through systemic redesign and innovative practices, and emphasizes on reduce, reuse and recycle. (Estarrona et al., 2019) Also a similar definition is that circular economy focuses on the "integration of economic activity and environmental wellbeing in a sustainable way". (Murray et al., 2017)

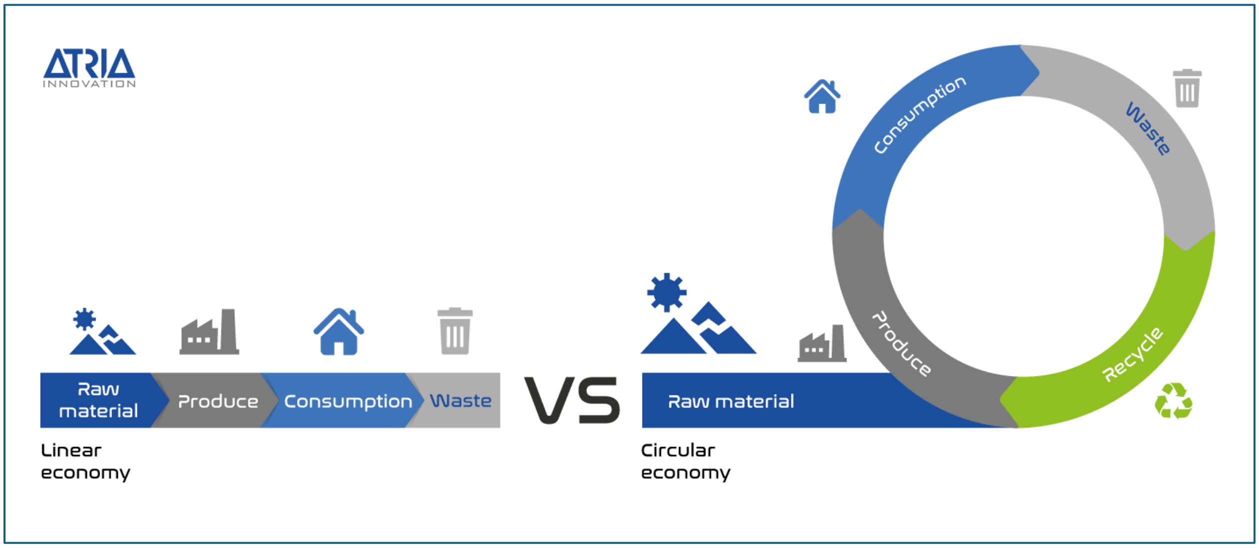

Figure 8-Circular Economy vs Linear Economy (Dev, 2024)

Reduce, is a cornerstone of circular economy and sustainability, which focuses on reduced material usage and reduced energy consumption. A crucial factor to reduce is the maintenance and repair activities. This is where AM technology provides the opportunity to repair the parts, which eventually will contribute to the reuse principle, as well. (Estarrona et al., 2019)

Reuse is about exploitation of used machines for another systems, which can reduce the manufacturing needs. Recycle, as a vital element of circular economy concept, focuses on efficient use of materials, to strategically reduce the need for further raw material extraction and refining them. (Liu et al., 2017)

Additive manufacturing technology has the ability to use recycled materials to fabricate new parts; for example, recycled metals can serve as the source for powdered metal utilized in metal 3D printing. (Florén et al., 2020)

Drawing a conclusion from described principles of circular economy and how AM can be utilized to play a key role in increasing material efficiency and contributing to the longevity of the spare parts, one can consider that investing in AM and promoting the use of it, is a rational and appropriate approach toward sustainability.

According to (Liyanage, 2016), a successful transformation toward sustainable businesses demands commitment, integrity, discipline, and a robust cultural foundation. This involves implementing a systematic and gradual approach that ensures profitability while also promoting environmental and social advantages. (Liyanage, 2016) describes those attributes as:

- Integrity—assurance of consistency in performance through policies, procedures, plans, etc., so that each party is aware of their own roles and responsibilities, what are their obligations, what they are accountable for, and how individual or team performance in turn affects business results.
- Discipline—the assurance that policies, procedures, and plans are adequately and seriously being referred to and followed in decisions and actions across all portfolios.
- Culture—assurance of internal receptiveness, and the sustenance of performance through cultivation of pride of achievements, promotion of ownership, rewards for accomplishments, etc.

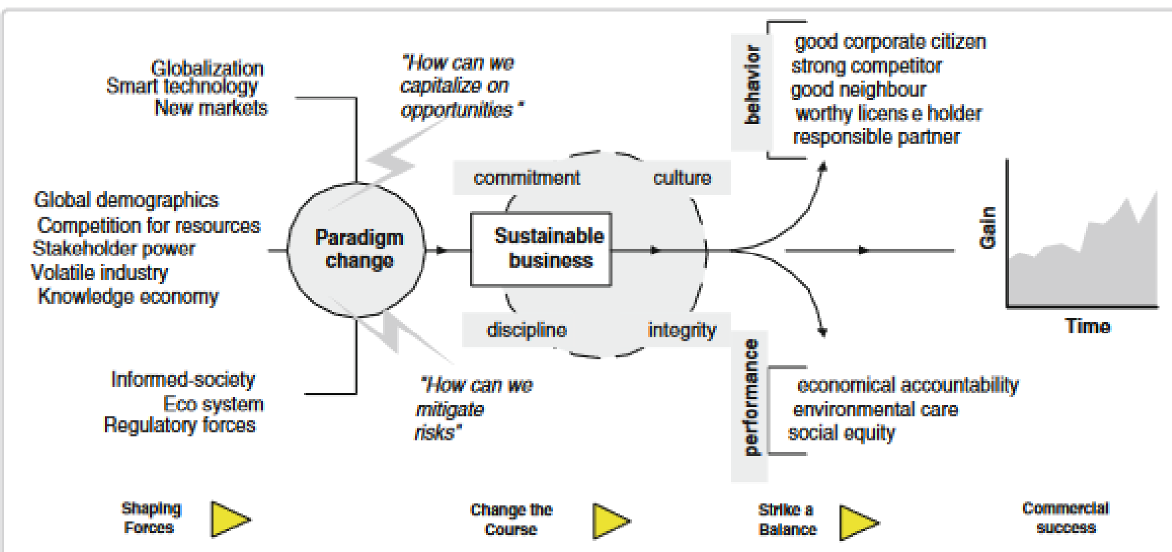

Figure no. 8, Sustainable business characteristics (Liyanage, 2016)

Thus, this transition towards a sustainable industrial ecosystem, which incorporates Additive Manufacturing and Digital Inventory platforms, requires a cooperative approach, with commitment to performance excellence, across enterprises. This strategy of consensus-building seeks to achieve a harmonious balance between economic, regulatory, and ethical aspects, so guaranteeing that business models are not only financially rewarding but also socially accountable. This comprehensive approach not only tackles present obstacles but also establishes a solid basis for sustainable development in the future.

4-10 New technologies

According to (Mellor et al., 2014), embracing new technologies is of great importance toward gaining an increasing share of the market among competitors and thereafter, being able to strategically address superior quality, lower investment in equipment, new product development cycles and lower inventories.

As (Meyer & DeTore, 1999) notes, “integration of markets, products, and embodied technologies is arguably the most difficult yet important challenge facing firms seeking continued growth.”

As mentioned earlier, AM is one of the core contributors to Industry 4.0 ecosystem, and as a result of its digital processes that is able to digitize the manufacturing processes, it is a highly capable and talented area, to be connected with new materials and other new technologies like Blockchain, IoT, and cloud computing. (Despeisse et al., 2017; Florén et al., 2020)

AM has already began changing the industrial landscape, however, the co-evolve of these technologies can be both challenging and rewarding for industrial organizations, as it will require them to rethink about and reevaluate their current business models, and facilitate a distributed architecture of supply chain, empowering both suppliers and customers, toward further value creation in the industry.

Among countless possible number of technological innovations that can contribute to a more systematic, innovative, and sustainable spare parts management that Digital inventory platforms can also play a facilitator role in further application of them, four relevant and interesting technologies will be mentioned here.

- 3D model generation via Deep learning:

Users can utilize the online design module of the platform's application layer to upload customized 3D models for printing. By harnessing the cost-effective computational power of cloud computing clusters, the Deep learning method of generative adversarial networks automatically transforms images taken from various perspectives into files suitable for 3D printing. (L. Zhang et al., 2020)

- Smart contracts:

Smart contracts are autonomous (self-executing) contracts that are responsible for the automation of invoicing and payments. Smart contracts are based on Blockchain and IIoT (Industrial Internet of Things) technologies, are able to withhold the terms of agreement between buyer and seller, being directly written into lines of code. In its simplest form, the smart contract is a computer program that resides in a blockchain, which can receive money from buyer and pass it to seller, if and only if the seller meets the requirement mentioned in the Smart Contract, i.e. upon conditions of the agreement being met. (Vigliotti, 2021)

In the context of spare parts management, smart contracts automate transactions and enhance operational efficiency by reducing the manual interventions typically required in traditional supply chains. This facilitates a transparent communication between involved parties, such as OEMs, suppliers and end users, and enables the real-time monitoring of contract progress based on actual improvements and reducing the probability of delivery delays or any possible infringements. (Hasan et al., 2020)

Equinor has also implemented this technology, in October 2022, via the collaboration of a company, Data Gumbo, to "automatically calculate and execute payments for Integrated Drilling and Well Services (IDWS) Day Rates for Johan Sverdrup and Troll assets." (Team, 2022)

- Digital Product Passport (DPP):

The digital product passport provides (stores and shares) essential information regarding product attributes, regarding its entire lifecycle. Such as the product origin, materials, repairability, accessibility to spare parts, usage guidelines, and proper disassembly or disposal methods. (Adisorn et al., 2021)

This technology aims to promote the culture of sustainable manufacturing and reinforce the transition toward CE, as well as creating a ground for further innovation and economic opportunities. This technology is mainly discussed with regards to enhancement of regional value creation within EU.

This is beneficial for asset manufacturers to collect complete product lifecycle information, for end users, to improve their decision making toward sustainability, and nevertheless, for regulatory bodies, as this technology offers traceability, it can enhance control over product certification and its compliance to different standards, be it locally, regionally or for a specific industry. (Adisorn et al., 2021; Saari et al., n.d.)

According to a study report by (Saari et al., n.d.), the advantages of using DPP are numerous, and the summary of it can be found in the following table:

Designers	Enhanced capability to integrate feedback from the middle and end-of-life stages into product design, such as improving recyclability and maintainability.
Manufacturers	Ability to collect comprehensive product life cycle information for uses like traceability for warranty claims and recalls, linking product flaws to manufacturing parameters, and predictive maintenance.
Repairs and Maintenance	Access to detailed technical information, product history, and spare parts data, enabling better service provision.
Remanufacturers	Access to critical information regarding components which can be crucial for effective remanufacturing processes.
Recyclers	Availability of detailed data on hazardous or valuable

	materials in products, facilitating safer and more effective recycling processes.
End users	Informed about various aspects of the product, such as spare parts availability, and CO2 footprint which supports environmentally conscious purchasing decisions and proper product handling.

Figure 9-Advantages of implementing Digital Product Passport

- Digital Twin

Digital Twin (DT) technology, which leverages sensors and data transmission, collects data throughout a product's lifecycle—design, manufacturing, distribution, maintenance, and recycling. Big data analytics processes this information to uncover failure causes, optimize supply chains, enhance product performance, and boost production efficiency. The cyber-physical integration facilitated by DTs bridges the physical and virtual worlds, allowing continuous data exchange and analysis. (Tao et al., 2019)

A DT is a digital representation that depicts both production processes and product performance. In 3D printing, DTs significantly reduce trial and error, mitigate defects, shorten design-to-production timelines, and lower costs. A DT of 3D printing hardware potentially can integrate mechanistic models, sensing and control systems, statistical models, big data, and machine learning. This integration contributes to minimizing extensive testing, mobilization costs for final product testing, streamlines part qualification, and enhances the lifecycle analysis of spare parts, which can contribute to increased overall performance, reliability, and sustainability. (Mukherjee, 2019)

5- Data Collection & Analysis

5-1 Data Collection

This section describes the data collection process used in this thesis, providing a foundation for a solid analysis of the thesis objectives.

Interview Guide

The interview guide was shaped based on a thorough literature review and consultations with several experts from Moreld Apply and academic advisors at UiS. This ensured that the discussions were steered towards yielding meaningful, informed responses aligned with the thesis objectives and practical insights. The questions were a mix of open-ended and closed-ended questions, aiming to investigate valuable insights from the expertise of the participants.

This approach was quite helpful, as it allowed a dynamic dialogue with the participants to investigate the complex interconnections between various influencing factors and delve into the industrial requirements and concerns of the stakeholders with regards to the utilization of Digital inventory platforms for spare parts management and the sustainability aspect of it.

Interviewing approach

To appreciate the participants' expertise and maximize the effectiveness of the interviews, some questions were reformulated during the discussions to enhance the quality and accuracy of the responses. Despite these adjustments, the structure and focus of the questions remained consistent across all interviews. Participants were informed before the interviews about the duration of the interviews and the anonymity attribute of their participation.

To ensure a focused interview and subsequently, the accuracy of the analysis phase, the interviews were recorded, with the participants' consent, firstly, by the initial communication with them and then at the beginning of each interview.

The interviews were conducted either physically or via Microsoft Teams, depending on the participants' preferences. Microsoft Teams was used with the student account, provided by the University of Stavanger. The duration of the interviews ranged from 45 minutes to an hour and 15 minutes. Therefore, all interviews were recorded and then transcribed to allow for a detailed analysis.

Participants were selected based on purposive sampling, aiming to include individuals with diverse roles, experiences, and perspectives. This technique, widely used in qualitative research, identifies and selects information-rich cases for the most effective use of limited resources, enhancing both the efficiency and validity of the collected data. (Palinkas et al., 2015)

This approach effectively included experts from diverse backgrounds within the Norwegian O&G industry — including operators, AM suppliers, an OEM, industrial consultancy firms, Standardization company, and various service providers — directly reflecting a purposive approach.

Participants' characteristics

Selection of individuals whose professional roles and expertise align closely with the study's themes and objectives was essential. Each chosen group of professionals brought a unique perspective to the table, contributing to a holistic understanding of DI and on demand manufacturing impacts on spare parts management in the Norwegian O&G sector.

This variety helps capture a broad spectrum of insights related to the implementation challenges, benefits, and strategic implications of these technologies. In total, 61 professionals were contacted, and ultimately 15 interviews were conducted, as many did not respond, and also a few people could not attend the interview due to scheduling conflicts.

The sample includes professionals from various companies and their relationships with AM, DI, and on-demand manufacturing:

Company no.	Company's role	Participants' role relevance	Experience of participant (in total- years)
Company no.1	OEM	Manufacturing Lead	25
Company no.2	Operator	AM Manager	10
Company no.3	Operator	Supply Chain Manager	15
Company no.4	Operator	AM specialist	3
Company no.5	AM Supplier	AM manager	3
Company no.6	AM Supplier	Manufacturing manager	22
Company no.7	AM Supplier	Technical manager	25
Company no.8	Digital Inventory platform	Product Manager	14
Company no.9	AM consultancy firm	CEO	23
Company no.10	Standardization company	Senior Manager	30
Company no.11	Service provider in M&M	Senior Manager	33
Company no.12	Industrial consultancy firm	Senior Consultant	30
Company no.13	Research institution	Senior researcher within AM	25

Company no.14	Service provider-3D Design	CEO	7
Company no.15	Research institution	Senior researcher within AM	10

Table 5– Participants' characteristics

Here is a visualization of the experience of the participants; notably, the average year of experience is high, as 66% of participants have equal or more than ten years of experience. This also contributes to the strength of this thesis findings, significantly enriching the analysis. This diversity in expertise ensures depth and a broad spectrum of insights, integrating technical, strategic, and operational perspectives, ensuring a relevant consistency with the thesis objectives.

Participants from various roles, including technical managers to CEOs, offer nuanced views on both macro and micro aspects of AM utilization and DI characteristics and settings. Furthermore, this variety not only facilitates a comprehensive understanding of current practices but also enhances robustness through cross-validation of data.

Including stakeholders across the value chain ensures a comprehensive view of industry challenges and innovations, making the findings relevant and actionable. This approach enhances research reliability, providing a multi-dimensional perspective that supports informed conclusions and industry-specific recommendations.

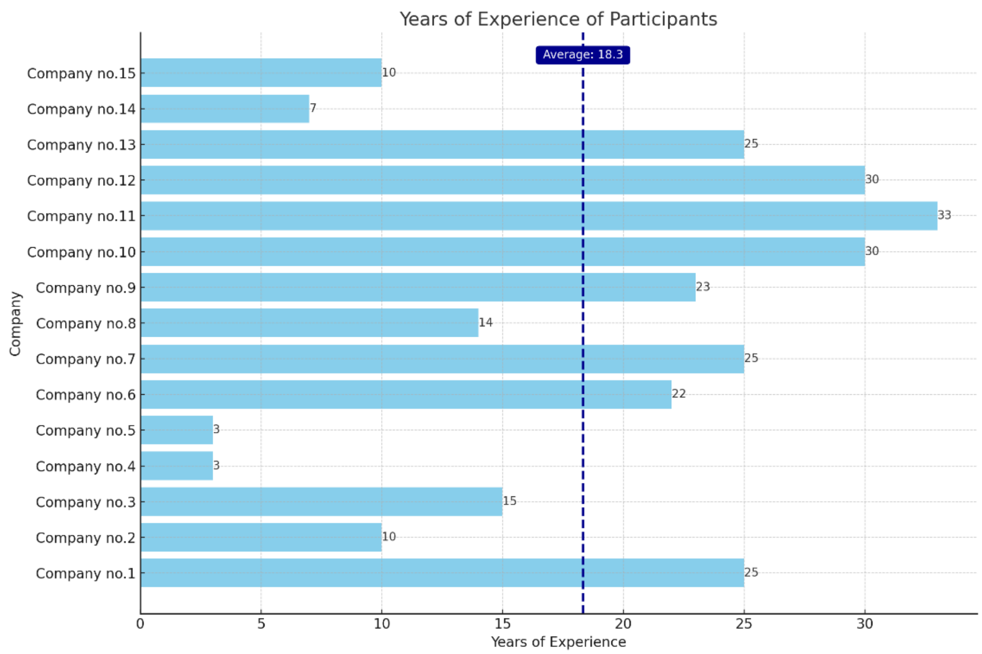

Figure 10- Participants' experience range

In some topics, a group of participants with more than 20 years of experience had similar opinions about certain subjects. During the analysis, they will be referred to as participants with higher experience, and their perspectives are frequently highlighted in sections titled 'Senior Insights'.

For the DI governance comparison, participants were introduced to different models through a visualization portrayed in section 4-7. The questions were close ended, but participants elaborated on their choices, engaging in dialogue to capture the main points of their preferences. Therefore, in the analysis section, the descriptions mainly reflect the outcomes of all gathered opinions.

5-2 Analysis & result

This section presents the findings from the interviews, incorporating and addressing the topics mentioned in the theoretical background chapter within the context of the Norwegian O&G industry. The chapter aligns the findings with the thesis objectives to create a comprehensive, traceable, and systematic flow of information. This approach ensures a robust understanding of each section while guiding the reader towards a holistic grasp of the themes. Each section describes the collection of responses in an integrated manner, investigating the influence of DI and on-demand manufacturing on sustainable spare parts management.

1- The first section focuses on the spare parts management challenges in the industry, with or without AM and DI, and suitability of printing spares based on NORSOK Z-008.

2- The second section focuses on the DI ecosystem, further opportunities and challenges of it in general. Analyzing the different formations of DI platforms, being centralized or decentralized, has been spread across the subsequent sections to provide a relevant and integrated understanding of these formations with respect to the other discussed concepts.

3- The third section focuses on the on-demand manufacturing opportunities and challenges, transportation, licensing, and dig into qualification status with regards to 3D printing of spare parts, role of DNV, and other related concerns here.

4- The last section is about the sustainability aspect of utilization of DI and on-demand manufacturing approaches, the customization level of spares, knowledge level, and discussing how the respondents believe in this regard.

Analysis approach

To achieve the best results from the interviews, a variety of follow up questions were included to effectively capture the insights of professionals from diverse technical backgrounds and with extensive industry experience. This interactive approach to data collection enhanced the depth of the gathered data. Overall, the case studies contributed to the generation of new insights rather than merely answering specific questions, offering a rich collection of material for detailed data analysis.

Furthermore, this approach guided the author to quantitatively use the data and visualize them with Python (version 3.11). The structure of the analysis mirrors the flow of the literature review, contributing to better traceability of the topics and increased clarity and understanding.

The analysis is based on a holistic understanding of topics while delving into details concerning spare parts management. It focuses on profitability and value creation for the AM ecosystem via DI and on demand manufacturing in the Norwegian O&G industry by decreasing costs, increasing productivity and utilizing new technologies for further sustainable developments.

Given the high number and diverse backgrounds of participants, the analysis section discusses the participants' opinions and draws conclusions using thematic analysis. Patterns were recognized and reflected, while specific valuable observations from individual participants or groups with particular similarities were highlighted throughout the analysis text. This method maximizes the effectiveness of describing the subject matter, using different examples from participants. For instance, all Operators refers to all the participating operators, or Service Providers known as Companies no. 9 to 15.

5-2-1 Spare parts management and AM

In this section, different opinions of stakeholders is reflected. The objective of this section is particularly to shed light on current spare parts management challenges in the Norwegian O&G industry, implementation of Additive manufacturing to produce spare parts, and analyzing the suitability of spare parts based on NORSOK Z-008 standard, to be stored digitally and printed.

Current spare parts management challenges

The recurring challenges in spare parts management identified by participants include locked capital of huge inventories of spare parts, high maintenance costs for material management in warehouses, an increasing number of spare parts in the inventories, long lead times, obsolescence, and inadequate documentation for large number of parts. These issues were widely mentioned. Additionally, unique observations were captured from participants' responses which are discussed below.

Supply chain disruptions and raw material shortages were mentioned several times as constant challenges in recent years due to various external influencing factors and geopolitical conditions, such as Covid-19 pandemic, Red Sea blockage, and the war in Ukraine. These disruptions have compelled O&G operating companies to adopt a just-in-case approach, with no alternatives, leading to the accumulation of large quantities of spare parts in extensive physical inventories.

Furthermore, Company no. 3 acknowledged that the entire management of spare parts is quite challenging for all operators in the Norwegian O&G industry. This complexity is based on the multifaceted nature of spare parts management as various factors such as spare parts' descriptions, technical specifications, prices, compatibility evaluation with existing equipment, and ensuring the uniqueness of spare parts descriptions and specifications are involved in the decision-making process.

Beyond these factors, the continuous updates on replacement strategies for spare parts as well as random failure patterns of them, also add to the complexity of spare parts management. Additionally, this company emphasized that effective spare parts management requires reliable digital tools, a systemic and holistic view of the involved processes, and effective collaboration between parties.

Companies no. 6, 9 and 11, mentioned that a considerable challenge is related to a fact that several operating oil installations in Norway are reaching to the end of their lifecycle, resulting in a large number of obsolete parts that are unlikely to be used later. Furthermore, when it comes to decommissioning of assets, proper and efficient management of large number of parts are crucial, whether the parts will be repurposed for other platforms or be directed for recycling at a very low price.

Additionally, these companies highlighted the loose partnerships between operators in handling of material management. For example, Company no.11 emphasized that the management of warehouses storing different equipment that belong to different owners has become a challenge due to insufficient sharing of parts among license holders, and that is also related to poor documentation for large number of parts, use of different standards, and a tendency to purchase new parts rather following a more sustainable way of repairing or checking for available alternative items in other warehouses.

Furthermore, Company no. 1 noted that old wooden tooling in some of their facilities has created casting challenges, causing production bottlenecks and consequently increased the lead time for spare parts.

Utilization of AM for spare parts

Thereafter, respondents provided a wide range of opinions regarding the opportunities and challenges of utilization of AM and DI for spare parts management.

The recurring opportunities identified based on participants' responses include, on demand manufacturing of spare parts, optimizing physical inventories, reproducibility and recycling of obsolete parts, repair services, 3D design optimization and customization for spare parts.

The majority of participants agree that utilization of AM for spare parts management is highly relevant and can be beneficial for the industry, as it enables on demand manufacturing of spare parts close to the end users, leading to significant decrease in lead times, logistic costs, providing a more stable planning horizon for maintenance engineers to ensure the availability of the production systems. And certainly, reduce the number of spare parts in physical inventories and decrease in all the associated handling costs. (contribution to demand forecasting)

<u>Service Providers</u> and <u>AM Suppliers</u> particularly emphasized on reproducibility of almost any type of obsolete parts via AM through various materials and sending those physical obsolete parts for recycling processes to produce, for example, metal powder to further use as a feedstock for production of spare parts via AM, which is completely aligned with circular economy pillar of recycle. (contribution to inventory management)

Recycling of obsolete parts has a two-fold positive impacts as it will reduce the inventory loading and material handling costs and allow warehouse owners to optimize the space in a more efficient and effective way and increasing their agility for further upgrades and addressing new needs and purposes.

Additionally, it was frequently mentioned that AM suppliers can produce new parts which their equivalent are not available in the market, nor the related OEM exists any longer, which is not only specific to O&G industry but similar for other industries and even fulfilling local demands.

For example, Company no. 5 described a case where they made flashlight holders for the Fire Rescue Station, “because they couldn't get it anywhere else. It was a part which is not produced anymore, but they still have the flashlights and they needed new holders for them.”

Thus, it can be interpreted that AM Suppliers can act as a reliable and agile problem-solver to provide parts for different industries.

Challenges

Participants also shed light on key challenges of extensive utilization of AM for spare parts in the Norwegian O&G industry. Among the challenges expressed by participants, the most frequent ones are related to,

- Qualification and certification process,
- Lack of standardization in certain areas of AM production

Regarding the qualification processes and AM standards, please review the detailed description in section 5-2-3.

- Lack of an operational hub for commercializing digital spare parts,

The lack of an operational hub to facilitate the connection between AM actors and end users properly, was elaborated on by the majority of Service Providers and AM Suppliers.

They believed that the order level is still low which is potentially because the awareness in the industry to new high-technological capabilities like their services is low and a robust collaboration or a hub to connect customers and end users with different type of needs to AM suppliers and service providers with various capabilities, is currently missing in the Norwegian O&G industry.

- Limited production capacity of AM suppliers,

Production capacity was another challenge that AM Suppliers and the OEM mentioned about. Both of which believed that production capacity of AM facilities is still quite limited and therefore, OEMs still cannot move the production of spare parts to them.

Thus, Companies no. 6 and 10, estimated that this situation is going to be addressed in the coming years with regards to better familiarity of AM manufacturers with qualification requirements of DNV as well as more companies are interested to investing in this area to build more production capacity and gain a market share here.

- Difference in mechanical properties between AM and non-AM manufactured parts,

The subject of difference in Mechanical properties between AM and non-AM manufactured parts was also discussed several times by the OEM, Operators and Service Providers. Company no.2, for example, added that for the additively manufactured materials, they are as good as traditional materials, but not the same, which require many of the materials to be tested again. They further elaborated that for some materials they will be chemically the same, but the microstructure will be different, thus, the design cannot be simply copy pasted.

- Identification of suitable parts for printing,

In a same way, Companies no. 2, 6 and 11, mentioned that, if the operators want to adopt the digitalization of spare parts, they need to start with a one-to-one drop and replacement, it means that for all spare parts that are in the storge now, a spare part is deployed in operation. Thus, in order to have a digital spare part, the printed part needs to meet or exceed the criteria of the deployed part. And if a company wants to 3D print that part, they will have to check different properties, be it part specifications, material qualification, production method selection, communication with the OEM, etc. Therefore, this situation highlights the importance of efficient identification of suitable spare parts for AM and DI.

Suitability of spare parts for AM

Furthermore, production of all sorts of spare parts with AM technology is not an efficient choice which amplifies the importance of suitability analysis to determine relevant candidates to be printed. Therefore, the price for Additively manufactured parts is an important and a real-world problem that participants were asked about their opinion whether the price of AM parts is a barrier for further implementation of the technology to respond to market demands or not, within the context of Norwegian O&G industry.

Based on the information collected, the key aspects determining the price for a part is whether high or not is dependent on the complexity of a part and how urgent is the need for that part. A directly influencing factor here is the end users' criteria for spare parts criticality based on their strategic and operational requirements and objectives.

The majority of respondents believe that when comparing one AM part with another part with the same functionality, made conventionally, the price is clearly higher. However, that is a challenge of seeing the whole picture because the cost reductions in various industrial areas is not calculated then, such as cost of storage, transportation (trips and related insurance), prevention of downtime, decreasing uncertainty and risk in the value chain.

On demand manufacturing for certain parts also contribute to an enhanced maintenance management strategy to plan with more precision to ensure assets' availability and maximum performance. Thus, the participants believed that if a thoroughly detailed study aims to compare these aspects of costs between an AM part and a conventionally manufactured part, it is highly likely that AM part price can be compensated with its other associated benefits such as decrease in lead time, physical inventory reduction and simplifying the procurement process.

With regards to the urgency factor, for instance, Company no. 4 (operator) described a case where they needed a strainer to be replaced as a modification, and then they needed it quickly. Then, a local mechanical shop, the original supplier, and an AM supplier, respectively offered nine weeks, six weeks, and three days as required time to provide the requested part. Thus, the company believed that the price in the O&G industry is not necessarily a primary concern compared to the assets availability, and performance reliability.

More interestingly, Company no. 5 expressed that based on their corporate management, competence, and AM technology level, they are able to produce parts with a relatively equal price to conventionally manufactured ones. Particularly, this shows that the competition between AM and other conventional manufacturing methods will be intensified in the coming years as the price for AM parts, which it was a renowned and significant barrier for AM parts, are gradually getting even.

Additionally, with regards to complexity factor, Company no. 5, similar to the majority of the participants, emphasized that not all parts are suitable to be printed and gave an example that for every engine or electric motor there is a need for some sort of shaft. Then 3D printing of those shafts are extremely inefficient because they are not complex parts and can be easily manufactured via CNC or even molding.

Suitability analysis for spare parts based on NORSOK Z-008 categories

Hence, the participants were asked about their opinions about the suitability of printing of spare parts, with an operational point of view, based on the current NORSOK Z-008 standard which is a highly relevant standard to ensure the safety of the operations in the Norwegian O&G industry. The standard, as it is discussed in detail in section 4-3, categorizes the spare parts into capital, operational, and consumable spare parts. The following bar chart presents the result of the preferable candidates for 3D printing.

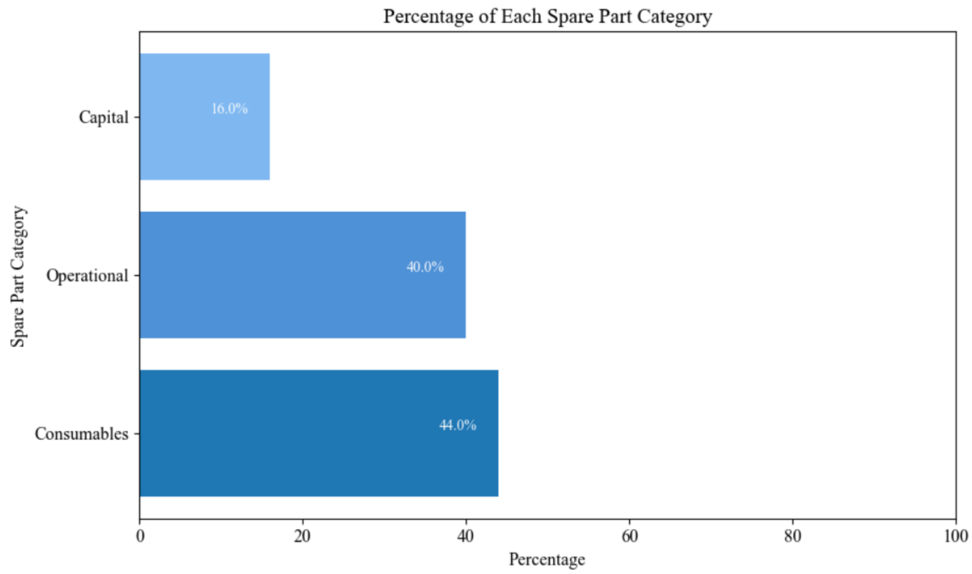

Figure 11– Preference for spare part for DI and 3D printing

The chart reveals the predominance of Consumables and Operational spare parts, indicating these are most favored for printing, implying the experts' view on the optimum resource allocation to accelerate AM utilization in the industry.

Companies no. 1 and 15, described that for consumables, use of polymer as feedstock, can drive more volume of printing parts, thus, facilitating a dynamic market for these parts. Also, Companies no. 9, 11, 13, added that the best approach, at least for early stage of industrialization of AM and operational establishment of Digital Inventory platforms can be consumables and some operational parts, as they are often smaller, used in high numbers, can be more favorably or cost efficiently produced on demand, and a very important part of it is that a large number of them do not go under IP protection and can be produced more easily.

Company no. 12, also highlighted that suitability analysis is crucial for operators, however, the operators have not allocated sufficient resources to proceed with identifying more suitable parts and this has made the AM ecosystem less dynamic and kept the order level for the parts still very low.

The respondent elaborated that with robust support from top management and efforts to enhance awareness and acceptance of AM across the industry, the suitability analysis can be expedited. This accelerated process will significantly impact the AM market positively, making it more dynamic and competitive. Consequently, this will lead to new innovations and increased revenue across the entire value chain.

5-2-2 Digital Inventory platforms

Awareness about Digital inventories and Digital inventory platforms from an operational perspective was quite robust among the participants, as they responded to the questions smoothly and comprehensively.

It should be noted that many organizations can potentially work with DIs in the Norwegian O&G industry, each employing different strategies to gain more market share in this ecosystem. However, from a supply chain point of view, the profitability of the supply chain is not the sum of the individuals' profitability, but how the whole value chain can adapt their processes to be more efficient and yet, effectively meet the customer demands to gain revenue to be able to exist and continue their progress.

With this point of view, aligned with the thesis objectives, the participants were asked about the strategic benefits of joining a Digital Inventory platform, and then their preference with regards to DI platforms' governance formations.

Strategic benefits

Regarding the main strategic advantages of participating in the DI platforms, respondents provided a wide range of opinions such as,

- The emergence of new profitable business models,

Company no. 2, expressed that the utilization of DI platforms will provide new innovative business models to store digital parts in which it can increase the optimum outcomes for both the OEMs and the Operators. The representative believed that in the new business models the OEMs only guarantee the availability of the parts, selling this functionality. Thus, the operator only print a part when it is needed (just-in-time) and also, they do not need to spend a big upfront cost to buy the large number of spare parts which some of those parts may never be used and consequently reducing the physical inventories' load, preventing the future obsolete parts, and essentially adopting a more efficient and sustainable approach.

Company no. 10, believed that DIs can help address IP issues and facilitate the process of 3D printing spare parts, as DIs serve as intermediaries that can connect the entity that holds the DI with those who need to print the parts. These platforms can simplify sourcing processes, where all AM Suppliers also agreed. Thus, these platforms would be able to streamline and manage all necessary communication and coordination between key stakeholders, ensuring efficient and secure processes.

Similarly, Company no. 12 also believed that DI platforms will bring most beneficial outcomes for the OEMs, and the solution, is around DI platforms and designing new contracts based on shifting to provision of some spare parts only digitally and by discussing the licensing terms between parties, so, they do not provide the printed spare part, but they give the right to the end user to do it.

Being relevant to this idea, Company no.11 described that when a company orders an equipment, they often do not have Buy Back policy, so they buy more than they need to ensure the availability of their systems, and usually many components will be left unused for the company. But then if a company have a Buy Back philosophy, then the OEM certainly needs to take the remaining ones back. Thus, it would be an incentive for the OEM to participate and cooperate with the DIs, instead of risking buying back a lot of equipment.

- Improved commercialization and coordination,

There was a consensus among respondents that commercialization of digital spare parts through DI is crucial for the industry at large, as it enhances coordination between customers and suppliers. These platforms facilitates easier access to suppliers with various technologies and customers with diverse needs, fostering mutual and productive cooperation among stakeholders. By streamlining operations and increasing coordination, stakeholders' expectations can become more aligned, leading to faster project execution with fewer obstacles. This in fact, mentions the importance of network effects of the platforms that its higher utilization level could eventually lead to progression of the platform in developing its processes to cope with stakeholders' requirements.

- Effective inventory optimization,

There is a consensus between all participants that utilization of DIs, will benefit both OEMs and Operators to have an improved ability to review their inventories in various locations and, thus, preventing waste and excessive costs yet establishing a strategic and effective digital connectivity between stakeholders in the Norwegian O&G industry which can increase the total productivity, performance and profitability of the value chain in the industry.

- Facilitation of approaching a robust on-demand manufacturing model

Please review section 5-2-3, for detailed information in this area.

- Promotion of a digital marketplace with more focus on sustainability

Company no.7 also added that they believe with participation in DIs, their achievements with regards to sustainability can be useful to attracts more customers to them and therefore, make a competitive advantage for them and thus, create a competition in the industry that in itself can lead to a possibility that other companies aim to learn from each other and thus, a soft cultural change toward sustainable development can be facilitated with utilization of DIs.

- Elimination of fake components

Company 8 mentioned a critical point that via DI solutions, fake components can be eliminated. They believe that because there are third parties between the OEMs and the end users, selling the parts indirectly, there might be a low probability that a bad actor in the supply chain sells a similar part to the original part to an operator. Thus, although the probability of such an event is low, the consequences are considerable. Therefore, with the use of DIs, more control and transparency for parts can be provided and the operators are directly working with the OEMs, under their approval either for parts or the associated AM suppliers to print the parts.

However, based on the current situation that the part designs are not still locked, and they are easily modifiable, Company no. 12, believed that originality is a key for success more than ever with regards to DI ecosystem. Because a company who innovates and creates a new product/service, they have established practical strategies, capabilities, and processes to do so, but the one who copies is always following their footsteps. Also, as the originality of the parts is an invaluable factor, for instance, in the aerospace industry. This approach must also be appreciated in the energy industry as well. However, with technologies like Blockchain or other digital services that can ensure the encryption of data, the concerns with regards to originality of parts might become more addressable.

Senior insights -1

Particularly the participants with higher range of experience, believed that utilization of DIs has great potential to increase the value creation in the industry by promoting a digital supply network capable of driving profitability, innovation, and sustainability in the industry. Here are three examples illustrating this perspective:

- Companies no. 9, 12 and 13 viewed DIs as gateways to an interconnected, digitalized manufacturing ecosystem. They believe that DIs can outperform the current linear and physical supply chain by mainly cutting many associated inventory management costs as well as increasing the agility and accountability in the industry. This is particularly true if DIs can leverage scalability and provide configurability to meet the diverse needs and requirements of various organizations both within and outside the Norwegian O&G industry.
- Companies no. 1 and 11, similarly emphasized that joining DIs will soon become a necessity for organizations to provide their products and services; and all who wish to stay tuned with the technological developments and maintain their competitive edge, they need to be proactive and adaptive to various changes. Thus, they believed the key to success is that organizations firstly, reach a good level of understanding about the AM technology and then identify their needs, match their “core assets and core competencies”

to harvest on the relevant capabilities of the technology that can offer added value for their operations.

- Company no. 6 particularly expressed that it would not be surprising for them if based on their highly technological capabilities, the improvements in broader utilization of standards, and increase in awareness within the O&G industry, 50% of their revenue could come from working with DIs within the next three years.

Challenges

Besides all the strategic advantages that DI platforms can provide, the participants were asked what are the barriers of broad participation in DI platforms and utilization of them in the Norwegian O&G industry. Based on participants' responses, the recurring challenges related to participating in DIs are identified as follows,

- Market Structure,

Companies no. 1, 7 and 15 believed that market structure is also an important factor and needs further consideration. This emerging paradigm influenced by AM in the value chain requires a change in the market structure as too much power is now on the buyers' side, which created a monopoly power with a single buyer. But if new demands from different operators increase, it is a positive sign that AM suppliers can assess the market in a better way and see solid business cases that they can provide services and products there.

They expressed that if operators even show some interest in this field, it can be helpful in stimulating the demand side. This has certainly also been related to the high upfront cost for AM suppliers to be certified for the production of spare parts, based on the criticality of them. Thus, If AM suppliers see the market is good and reliable, they will be encouraged to invest to become certified. Otherwise, it is too risky for them to enter a market that only Equinor is the main buyer.

- Existing Business Models of OEMs,

There is consensus between all interviewees that existing business models of OEMs are based on mass production and their willingness to adapt their business models toward providing digital spare parts depends on their digital infrastructure as well as finding or shaping reliable commercialization models with operators, with the utilization of DI platforms.

Another important factor mentioned by several participants is that OEMs do not risk moving their production toward the AM suppliers as their capacity is very limited. For example, Company no.6 expressed that AM suppliers in Norway has around only two percent of the current production capacity of an OEM, but if this capacity grows to 30 percent, then OEMs can evaluate the options to move a proportion of their production to them.

Company no.12 mentioned that OEMs are afraid of strategical implementation of additive manufacturing while, with a proper and clear communication with the stakeholders in the network they can reach a safe licensing option for specific digital spares. However, the representative mentioned that 3D scanning is a real threat for OEMs, because bad actors globally can disrupt the originality of their products. Therefore, their proactive presence in the DIs can also be beneficial in adapting to new paradigm and increasing their market share from this opportunity of DIs.

- Digital Infrastructure and Technology Readiness of organizations,

It was consistently mentioned by the majority of participants that the systems and interfaces that can communicate digitally with DIs are not in place in the organizations within the industry, as well as the technology readiness in organizations is not well addressed and their current digital infrastructure cannot maintain an effective connection or integration to new digital platforms like DI platforms.

- Data Security and IP Protection assurance,

Participants consistently highlighted the lack of a reliable IP protection solution as a substantial challenge, with cybersecurity being crucial for DI platform acceptance. Companies no. 12 and 13 noted that data security is becoming as important as IP protection, especially since copying original parts is now easier as, for example, CAD files do not have watermarks on them. Company no. 8 believed that these concerns are addressed in their platform's processes, and they are developing the cybersecurity of the platform, however, many OEMs are still afraid of entering and having more active participation in their platform and in general in digital supply network.

- Accessibility to Certification and Qualification information

As it was mentioned earlier about the importance of qualification and certification, almost all participants expressed their concerns about the availability and ease of accessibility to AM suppliers' and spare parts' qualifications' information in the DI platforms.

DI governance

Furthermore, participants were asked to share their opinions on comparing the two Digital Inventory platform formations regarding their ability to facilitate an efficient, transparent, and secure flow of information between stakeholders—in a word, information management. Their preferences are as follows:

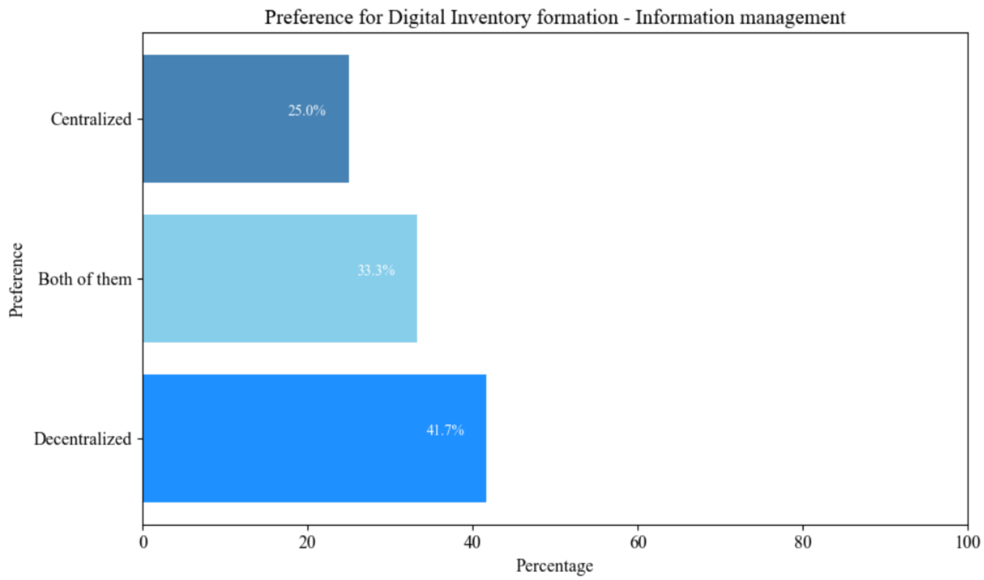

Figure 12-Preference for DI formation – Information management

The primary themes identified from the dialogue with participants about the reasoning behind their preferences are reflected here:

- Transparency

Companies no. 3, 4, 12, and 13 expressed that the definition of data transparency varies for different stakeholders, which could present some challenges. Additionally, Operators noted that transparency should not mean revealing what they are buying. They also mentioned that decentralized formation might complicate matters, as some parts are shelf-made, and some are custom-made. Therefore, in this regard, they prefer access to a centralized digital inventory.

- Revisions control and modification for digital spare parts

Companies no. 6, 12, and 15 highlighted that with a decentralized formation, feedback for parts can be more easily transferred between parties, emphasizing the interconnectedness of data across the platform. For example, if an operator sees a problem with a spare part and want to get a new design, it would be easier for them to be in more direct contact and connection with the OEM. This opportunity can also be harvested for further innovation-driven solutions for customization and use new/mix materials for spare parts and for repair operations.

Company no. 1, the OEM, emphasized that, “in our perspective, revision control is a high priority topic for DI platforms, IP and licensing subjects.” The representative continues to describe that considering the current two major centralized DI platforms in the industry, within the next five years there might be more than ten of such platforms, then in fact OEMs need to have a revision control whenever they want to redesign a spare part in their system; then the respondent added that, “To have control of several platforms with several the same parts, we don't want to upload thousands of parts and then we have to have revision control of all of them which requires a lot of man-hours and then we cannot just throw around our production drawings in several platforms”.

The OEM representative believed that with a properly organized decentralized DI platform that can communicate with their digital systems more directly; to prevent revision control with several centralized platforms, it could streamline efficient operations and would be the favourable choice for them and it can also increase the visibility of the transactions between the them and the buyers who want to get access to a digital spare part.

- Digital infrastructure compatibility

Companies no. 6 and 10 believed that decentralized digital inventory requires more advanced digital infrastructure from stakeholders (such as small OEMs or service providers) which are not currently in place. They noted that implementing such infrastructure would be expensive, and companies' investment in digital infrastructure is still steady and may take some time. Therefore, for the initial utilization of DI and AM, a centralized formation may be more suitable. They also added that with a centralized digital inventory platform, the costs of using the platform and even the qualification process could be more easily distributed, facilitating the formation of the value network.

- Customers’ demand variation

AM Suppliers emphasized that these platforms would coexist in the future, and they believed because the customers’ demands are varied in the industry, both of these platforms must be there to solve the problems and facilitate the on-demand manufacturing of spare parts. For example, Companies no. 6 and 7 described that to address different tasks and different applications, different solutions are required, and both of these platforms can be useful, as some OEMs or operators have their own restricting policies with regards to cloud platforms, and therefore, with availability of both platforms they can provide solutions more efficiently.

- Participation incentive

Companies no. 2 and 12, highlighted that from a purely production standpoint, they prefer decentralized formation as every stakeholder keeps their own rights and they have simple incentives to be in the platform, while the centralized platforms are required to justify the benefits of their services to getting companies on board. Therefore, a capable decentralized platform would already benefit from this basic condition. Both of these companies mentioned that as actors need to pay a fee to get in the centralized platform, this is a limiting factor for further participation in their platform and can also increase the overall costs for participants as well as acting as a barrier for different small businesses to join and add value to the ecosystem.

The OEM and majority of the Service Providers agreed with this opinion and expressed that decentralized formation could increase OEMs' control over their designs and thus, encouraging them to have better engagement in the digital supply network.

Moreover, Company no. 14 believed that a properly designed decentralized digital inventory platform will provide the stakeholders an opportunity to have more control over their data and software solutions and also will let them to adopt a modular approach in fulfilling orders for different customers with different needs, enabling them to prepare themselves for future customization requests, also emphasizing the data-driven insight

- Central Control and responsibility

Company no. 6, added that many OEMs have still very low knowledge level about AM and the DIs and to address this situation, a centralized DI platform that can organize the processes with clarity and central responsibility can be favourable. However, as their knowledge increases, they will probably be more inclined to join the decentralized DI platforms as they could have better control over their processes and invest in customization of spare parts more effectively.

Company no. 1, the OEM, also expressed their concern about the validity and credibility of the decentralized digital inventories that are going to be connected to the decentralized digital inventory platform. Because in fact the platform then is acting as a hub and proper key acceptance criteria for participation must be implemented from the decentralized DI platform owner to address risk management and control over the qualification of the participants. Hence, a centralized digital inventory platform can have an advantage of central responsibility to follow up and resolve the possible challenges between the parties.

Senior insights -2

Particularly the participants with higher range of experience, believed that a single huge digital inventory platform cannot be the only source for all sorts of digital spare parts, therefore, the industry will eventually need various options and platforms to address different needs of different stakeholders, that it seems decentralized digital inventory platform have a better position due to their inherent flexibility.

They mentioned that at some point in time centralized formation may be unable to scale and would limit the innovation. They mentioned that some centralized digital inventory platforms tried to implement pre-defined solutions which is not aligned with open market principles as innovative solutions are created based upon a need, and if they go in reverse, they are limiting the innovation.

An interesting relevant example, from Company no. 9 is that “If you relate this to book sales, can you make a global bookstore that has all the books in the world and nobody should buy books anywhere else, because they have all the books? So, companies like people need options for other books, other prices, and the other alternatives.”

Several senior managers (including companies no. 1, 6, 9, 10, 11, 12, 13) emphasized that because of the existence of multiple centralized digital inventory platforms in the future, and because the processes are not necessarily streamlined to stakeholders’ end instead controlled by centralized platforms owners, there might be a challenge for OEMs and service providers in further customizations and updating revisions for products, as they need to do the revision for certain number of parts in several centralized DI platform, and it is kind of duplication work, and need a lot of man hours which it would be an inefficient approach. They added that DI platforms should act as an entity to “debottleneck” and not adding more bottlenecks or inefficient processes.

5-2-3 On demand manufacturing

In this section, according to the thesis objectives and related contents in the theoretical background, in section 4-8, participants’ opinions regarding on demand manufacturing utilization in the Norwegian O&G industry, IP licensing for spare parts, qualification processes, how DI formations can contribute more to the qualification processes, and influence of DI formations toward facilitation of cluster of 3D manufacturers, is collected, and analyzed.

Regarding on demand manufacturing and localized manufacturing, there is a consensus between the participants that on-demand manufacturing of spare parts for the O&G industry is still in the early stages of development and as demand and use cases increase, these technologies are expected to mature as well.

Additionally, with regards to the engagement of OEMs to adapt their existing business models to AM technology and Digital inventories, approximately all participants appreciate the leadership of Equinor in shaping demand pull and pushing the AM technology, basically, promoting AM culture in the Norwegian O&G industry.

Subsequently, regarding the licensing for digital spare parts, Companies no. 1 and 8 described that there are very good OEMs in Norway and these Norwegian OEMs have shown more engagement as a result of continuous collaboration with operators directly and indirectly by their presence in different conference panels and industrial exhibitions in Norway. Thus, it is more probable that these OEMs would be the first ones to adapt their business models to a more digitally driven industrial ecosystem.

Qualification process

Furthermore, the participants were asked about whether they see a lack of standards and regulations within the AM field in the context of the Norwegian O&G industry.

Company no. 1 mentioned that API and DNV standards are relatively unfamiliar to many companies, as they often rely on their own in-house qualification standards, which are not globally recognized O&G standards but rather factory standards. Therefore, qualification is essential for building trust in AM parts and DIs.

All participants fairly believed that DNV has provided the industry with relevant and practical qualification standards, however, the standards are not utilized broadly and the AM suppliers' competence regarding using of them is still insufficient. They pointed out that as AM utilization is scaling up and the industry need to assure the reliability of AM parts to prevent negative consequences, and these standards are established to contribute to safe operations and a reliable supply chain in the industry. Several themes related to the qualification processes were identified as follows:

- Key acceptance criteria for Additively manufactured end products

Several participants emphasized the industry's need for adequate standards to clarify the key acceptance criteria for additive manufacturing, particularly concerning polymer materials. Company no. 1 highlighted that while some materials for metal are generally acceptable, provided by DNV, there are no defined acceptance criteria for polymers according to a standard. They pointed out that DNV qualification and API guidelines only specify the process, not the acceptance criteria for the material itself.

Similarly, companies no. 2, 6, 8, 13 voiced concerns about the certification of many materials due to their microstructure characteristics, as even if the materials are identical, the final AM product might not meet DNV standards.

- Investment issue

Based on participants' opinions, it became clear that the high upfront cost of qualification is a significant barrier for AM machine owners. Almost all participants, including Company no. 10 and the majority of Service Providers, highlighted that the substantial upfront investment required for the qualification processes is challenging, and since it may take around a year, AM suppliers are uncertain about the profitability timeline given evolving market conditions and demands.

Also, Company no. 1, the OEM, emphasized that AM suppliers need a focused business plan. For instance, if they qualify for titanium, they must concentrate on titanium to ensure profitability.

- Communication with operators

AM Suppliers mentioned that there is always a technical discussion at the beginning between them and the operators on qualification levels. For company no. 6 that is qualified with AMC-2 level, which is the second level of criticality based on DNV-ST-B203, they see some challenges in this regard, but they mentioned with an open discussion with relevant responsible technical teams and their discussion with a DI platform they could solve the challenges and the process is getting more straightforward, as well as they appreciate the clarity and practicality of the DNV-ST-B203 standard.

- Role of DNV

Companies no. 2, 6 and 10 mentioned that with the upcoming release of part family standards, there is a good opportunity to reduce cost and time on qualification, as this type of standard allow for certification of the parts with different sizes between two large and small sizes of parts, where it eliminates the need for qualification process of hundreds of valves which essentially, they are based on same material and process but with different sizes.

All participants believe that more engagement of DNV in DI platforms will enhance the accountability of these platforms and thus bring trust to these platforms for enhanced scalability of these platforms and contributing to the industrialization of AM to respond to the demands from the Norwegian O&G industry.

DI governance for qualification process

Furthermore, it is important to know that, although the qualification process as of today is followed outside of the DI platforms, DNV is working on a new service, called on-demand qualification that technically is possible to be integrated into the DI platforms. The participants were asked about their opinions about whether any of Digital inventory platforms can facilitate the qualification processes, and the result is as follows,

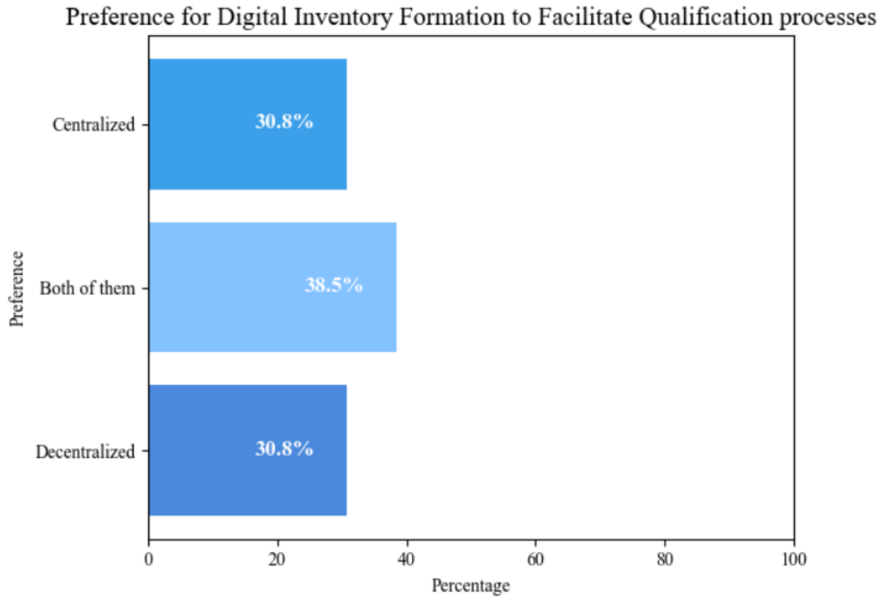

Figure 13-Preference for DI formation – Qualification process

The themes discovered here are:

- Transparent collaboration

The participants mainly from AM suppliers, believe that centralized digital inventory formation is more probable to facilitate the qualification process, because they believe that this formation facilitate a space for transparent collaboration between stakeholders and knowledge and data can be easily shared which in fact can make the technical expectations from stakeholders more uniform which can help AM suppliers to run the projects with more agility.

- Standard mix challenge

Also, Company no.3, expressed that the decentralized digital inventory as it promotes AM facilities to qualify their part separately, there might be a challenge of dealing with different standards for same parts in the industry that may lead to some risk and compliance.

With the new DNV service of on demand qualification, it was mentioned by several participants that centralized DI formation can be more useful as it is more focused more centralized, they can share the costs of qualification and infrastructure. It was mentioned as well that DNV promotes multiplatform digital inventories, as long as they are satisfied with their capabilities, confidence being maintained, they will approve the DI platforms.

- Both of the DI formations

Mainly operators believe that as the qualification process is taking place out of the DI space, both of the formations can be useful in different cases. quite similar, have been able to qualify the high criticality parts, on demand repair mostly, it depends, set by operators, we know the requirements for first and then the OEM should know at the first, as long as they are all on board, both can work.

- Flexibility and Innovation:

Company no. 12 emphasized that a decentralized DI formation should have no restrictions, allowing parts to be digitally integrated into the system. This approach ensures cost-effectiveness, quality, and timely delivery. The decentralized model lowers entry barriers and fosters innovation by providing broader network access without the limitations imposed by a centralized system, which could raise costs.

Company no. 14, highlighted the modular nature of decentralized DIs, where each DI can function as an ERP (Enterprise Resource Planning) and CRM (Customer Relationship Management) system simultaneously. This modularity allows for seamless integration with entities like DNV and other laboratories, ensuring a tailored approach to supply chain management and qualification processes.

- Route and Partner Selection:

  Company no. 11 and 12, added that a decentralized DI formation allows OEMs to choose more freely from possible routes and cooperation partners, which is essential in following equipment and processes tailored to specific needs to achieve efficiency and effectiveness in the qualification process.

  A decentralized DI gives the ability of organizations to manage their operations independently. This way, organizations can control their qualification practices much more efficiently and manage them on their own end. By virtue of this method, the management of projects, such as redesign, choice of material, and order management, is made easier through connection with other systems in tailoring services specific to customer requirements.

- Limited number of AM suppliers

The OEM expressed that because the build process qualification is critical and only a few are certified now, for the short term, it is more viable to use centralized formation, but when the build process qualification (mentioned in detail in section 4-8) gets more common and then more parts will be produced, then a decentralized would be more useful. Because, then they would put a part up in a DI and for example three suppliers could quote it and they will be able to pick and choose the best price or best delivery time.

Licensing for spare parts

With regards to the challenges of on-demand manufacturing discussed in the section 4-8, here the participants were asked about their opinion about licensing for digital spare parts and the optimal scenario of implementation between fixed fee only, royalty fee only or mix of both.

The majority of participants were familiar with the idea of “licensing for spare parts”. However, a few participants were introduced to the term details and afterwards they provided their opinion about it. Approximately, all the participants believed that for the early stage of implementation of DIs and on demand manufacturing, it is more likely that an optimal approach toward licensing would be the mix of fixed fee and royalty fee. It is revealed then that determining licensing approach is based on the part quality and the cash flow management of both seller and buyer sides.

Strategic benefits

Companies no. 8 and 10 discussed that using licensing for spare parts is a promising yet complicated approach, where various factors are involved, such as part durability, type of the part being operational or new products, investment of OEM for production of those parts, strategic relationships, and level of trust between OEMs and AM suppliers and end users, cash flow management, etc.

These companies believed that mixture of fixed fee and royalty fee for licensing is more relevant because in the context of digital spare parts, there would be certainly a fixed fee for those parts as OEMs would provide the original design itself and the revisions for the parts, and yet they ought to gain revenue per-print of a digital spare part in the form of royalty fee, which is approximately a same approach that it was discussed in section 4-8.

Mainly AM Suppliers, the OEM, and majority of Service Providers expressed that adopting a license with mixed of both options, and then fixed fee only can be more preferable than royalty fee only, as the OEMs need to ensure a planned and stable revenue and cash flow if they want to move a proportion of their production to AM suppliers. Furthermore, AM suppliers can also benefit from this approach, because based on the high upfront costs due to qualification processes and high expenses for maintaining their AM machines, they need a stable revenue to continue their business as well.

Company no. 2 believes that adoption of licensing approach would be profitable for operators as it will eliminate the huge upfront costs for spare parts and have a positive impact on optimizing the physical inventories, as the digital parts are licensed.

Particularly, Companies no.1, 5 and 12 believed that implementation of licensing approach toward digital spare parts can be quite beneficial for OEMs, as they only provide the digital spare parts and most of the associated conventional production of physical parts will be eliminated for them. These companies also agreed that adopting this approach could offer the opportunity that OEMs to keep their production lines and focus on planning to produce exclusive and innovative products yet receiving stable income from their licensed digital parts.

Challenges

Company no. 11 and 12 believed that OEMs are still hesitant as their existing business models are in place and have a skin in the game, and they are unsure about the buyers' side and also the associated risks of sending their designs over the internet. This is also highly relevant to market structure as mentioned earlier with regard to current challenges of utilization of DIs, mentioned in section 5-2-2.

Another challenge mentioned by Company no. 4 is the difficulty of changing existing contracts for spare parts with the vendors. However, the representative expressed that the company is determined to include the provision of digital spare parts in their new agreements with vendors.

Cluster of 3D manufacturers

The interviewees provided insightful perspectives on the utilization and potential of on-demand manufacturing via a cluster (hub) of 3D manufacturers in the Norwegian O&G industry.

Company no. 8 described that localized manufacturing introduces challenges, particularly when implementing new processes for component production. For example, when OEMs design and manufacture components like valves using traditional methods, they produce large volumes and keep proprietary machining methods confidential. In contrast, additive manufacturing (AM) requires sharing detailed design information, even for single samples. This shift from mass production to potential one-off items necessitates significant adjustments in operational strategy and OEMs' business models.

Company no. 14 specifically described that based on the inherent flexibility of AM to respond to supply chain disruptions, the 3D cluster can be mobilized at short notice for different industrial purposes.

Almost all participants emphasized that competency is crucial for safe, reliable, and efficient on-demand manufacturing of spare parts in the O&G industry. Companies no. 4 and 6 discussed that the process is not yet streamlined and often sending the parts to testing facilities undermine the on-demand manufacturing approach. Within the context of on demand manufacturing, all interviewees agreed that regional transportation would increase while abroad transportation would decrease significantly.

Furthermore, the participants were asked which of the DI formations could facilitate a robust cluster of 3D manufacturing, and the result is as follows.

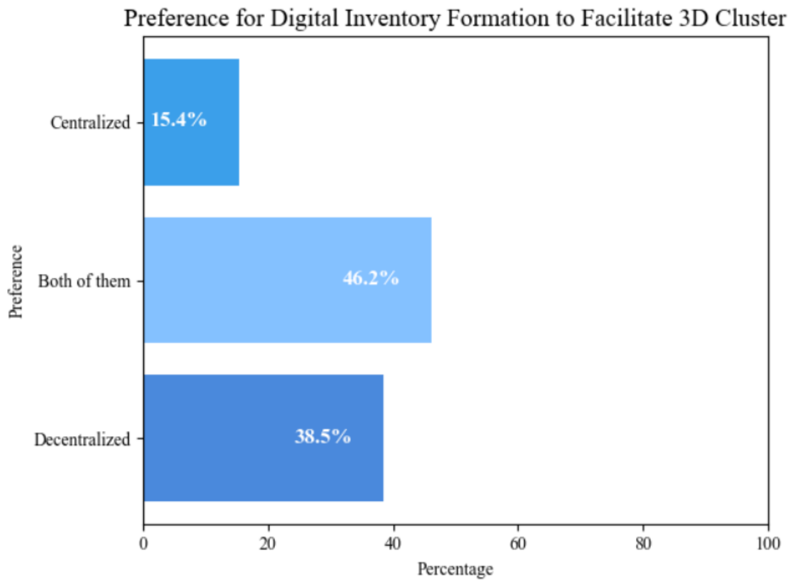

Figure 14-Preference for DI formation – Cluster of 3D manufacturers

In the analysis of preferences for Digital Inventory (DI) formations that can facilitate a 3D cluster manufacturing, it was crucial to capture the perspectives of various stakeholders within the industry. Here, it appears that while there are varied opinions on the optimal DI formation for facilitating 3D cluster manufacturing, the overarching priority is to achieve a system that balances control and flexibility. The findings underscore the need for a DI formation that can dynamically support the complex and evolving requirements of the oil and gas industry.

Several participants, mainly with higher range of experience, believed that to have a robust 3D cluster, it will be the decentralized. They described a risk that in the centralized formation the OEM is linked to the factory, and then if many parts are stored in a centralized DI, then if that platform owner decide to shut down or go bankrupt, what will happen to the files? There is a serious risk here, both for the OEMs and operators. Thus, decentralized would allow a local network of decentralized digital inventories matching the demand and supply more naturally.

5-2-4 Sustainable development

The participants were asked about their opinions on the sustainability aspect of utilization of DI and on-demand manufacturing for spare parts management. Because the economic aspects were discussed in previous sections, now according to the literature about sustainability in section 4-9, the focus here is more on the environmental and social aspects of sustainability, which are interconnected to each other. This is presumably the reason that the term “sustainability” is used, as all the three pillars are interconnected together and lack of attention and effort toward any of them would not lead to a long-term and result-oriented value-creation.

Environmental aspect

Based on participants' responses, main recurring contributions of DIs and on demand manufacturing to environmental sustainability include,

- Repair services

There is a consensus among all participants that with proper utilization of AM and DI, one positive step toward more sustainability of spare parts management is to reduce buying large number of spare parts in batches that some of them may never be used, a linear economy approach, that asks for more extraction of raw materials and depletion of natural resources while being an influencing factor on incremental price of materials in the market in the long term. This means that approaching circular economy principles with the use of new technologies like AM can increase efficiency of value chain and yet effectively contributing to all three pillars of sustainability.

Regarding repairing services, among Service Providers, Companies no. 9 and 11, emphasized that, "the oil and gas industry have a long history of just replacing instead of repairing", and they pointed out the necessity of "Culture Change" to keep the industry resilient and profitable to contribute to sustainable value creation on the NCS. Thus, utilization of AM for repairing of capital spare parts is a common point mentioned by the majority of participants, while more exclusively and extensively by AM Suppliers.

Company no.3 gave an example that they recently approached an AM supplier to repair a part, but they have some challenges with regards to the repair time for the part. Regarding this issue, it was discussed with Company no. 6, and they believe the repair time depends on many factors, but mainly on the criticality level of the part, that if it does not need qualification the part can be repaired in around 14 days, otherwise it will take another two weeks.

AM Suppliers strongly believed that repair services can have a massive positive impact on environmental sustainability of spare parts management, as it will reduce the need to order new parts, and thus proactively preventing all subsequent costs and challenges of ordering of new parts.

Company no. 6, for example, explained that around 60% of their operations are related to repairment of critical parts, and emphasized that repairment with AM provides significant environmental benefits. This company also mentioned a lack of good research in this area is a challenge to showcase a range of benefits of repairing with AM toward positive sustainability outcomes.

- Design enhancement and Customization with AM

In this regard, interestingly, all participants mentioned how AM could be used to potentially upgrade the design of spare parts beside the main action of repair to enhance part performance and extend the asset lifecycle, which is completely in line with circular economy practices, instead of ordering and purchasing new parts.

For example, Company no. 8, described a case where a customer could not find a specific type of fan because the corresponding OEM stopped making those models, and they were not allowed to run the motor without the fan as well. Thus, Company no. 8 designed a fan while included a comparison between the old fan design and how it was damaged, and they upgraded the design to increase the thickness of the fan to improve its tolerance and resistance when operating in harsh environments. This was a quite cost-saving option for their customers as the price for that fan was just 500 USD, while the new complete system of motor would cost 10,000 USD.

Within the same context of customization of spare parts, Company no. 13 also expressed that although the customization of spare parts today is very low because it is mainly based on the inventories, the potential of doing so is incredible, because with customization the designer will make sure not to produce spare parts with the capability that is more than actually is required.

For instance, if a pump is needed, the design would be customized in a way that a produced pump should exactly have a determined capacity and energy consumption that it is needed for the task and not something with redundant capacity or redundant/over consumption of energy. Customization can address end users' specific requirements for spare part based on the operating conditions like location and time for a spare part. Furthermore, it can lead to material consumption optimization of parts, which the advantage is two folded, one reducing the final product cost and then it is also aligned with Circular Economy pillar of Reduce.

All Operators also expressed that because their portfolio will get stronger in the future and the need for innovative solutions is increasing while trying to make the processes more efficient, as well as operational challenges in aged installations, the need for more customized parts is expected to increase significantly in the future.

Company no.1, the OEM, estimated that the demand for customization services will increase in the future, because from a production point of view, the process of modifications with casting usually is lengthy and takes so much effort for coordination between the design engineers and the foundries, while with AM the modification is accelerated, and they can get exactly the capacity and functionality they want with more speed.

Furthermore, the OEM representative described that the AM technology maturation in the recent years has been a great positive factor that made the AM production a viable choice for customization of spare parts; because for example, with new AM machines that are equipped with 16 lasers, they can produce a part in a very short amount of time in approximately ten hours compared to an AM machine with one laser needing 100 hours.

Thus, it becomes clear that they would have around 90 hours difference in costs to run the machine and subsequently means that as the production speed goes up, the price will go down for customization of spare parts, and this can have a consequential long-term impact on reliability of operating systems and sustainability of spare parts management in the Norwegian O&G industry.

Customization level for spare parts

Furthermore, as discussed earlier regarding the advantages of part customization with AM, participants were asked to rate the level of customization of spare parts in the industry on a scale from 0 to 5. The result is as follows:

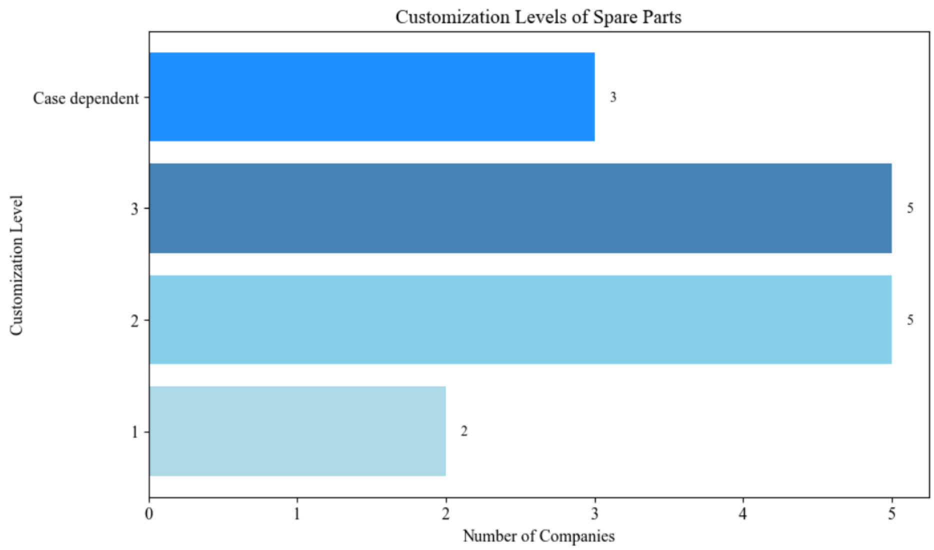

Figure 15-Current customization level of spare parts

Based on the collected data, opinions on the current level of customization of spare parts in the industry vary significantly, with ratings ranging from moderate to slightly above moderate. Several responses indicate case-dependent scenarios, reflecting a balance between standardized processes and adaptability within the industry. Those who expressed customization is case dependent, were mostly believed that the customization level is around 3, while if OEMs accept to cooperate with regards to printing the parts, high customization level is quite accessible with current AM technology maturity, for example with Power bed fusion technology.

Moreover, regarding the case dependent opinions, the main dependencies mentioned by the participants are related to whether it is about obsolete parts and standardized parts, new products from AM suppliers, and furthermore, the adaptability of OEMs to accept AM as a valid production method.

Operators and majority of Service Providers expressed that there are many standardized parts in the O&G industry, thus, operators require the same parts, and they have no time, mainly, to check and analyze whether some parts or obsolete parts can be manufactured with better performance or not.

On the other hand, AM Suppliers said that based on some new operating conditions and various problems that have not met before by different operators (demand for customization), they produced new parts which were not made before and delivered them to solve the problems and improve performance or offer new functionalities.

However, for both scenarios, as Company no.13 mentioned, "they need to certify the parts and qualify the new version, and that costs massive money and costs time, which is a clearly limiting factor."

- Digitalizing obsolete parts and then the possibility of recycling them,

On the other hand, regarding the obsolete spare parts the Operators believe that these obsolete parts can be 3D scanned and then stored in digital inventories, if they don't go under IP protection, otherwise, communication with the OEM is required, and then they can be scarp and recycle those parts. Also, they believe the number of these obsolete parts at the discretion of Operators in the O&G industry is very high.

The participants were asked about whether they see a possibility that AM repair services would become one of the main services in the DI platforms, and approximately all the participants welcomed such possibility and believed that it is highly relevant, either when talking about comparing old design and new requirements for a precise repair operation and possibility of enhancement and also whether the repair operation could be either on site or at AM facilities.

- Energy efficiency in transportation,

Energy efficiency is another interesting point about AM products which circles back to the technological attribute of AM in producing parts additively, and using less material, ultimately making the end products lighter than the conventionally manufactured (subtractive manufacturing) peer ones.

This means that vehicles can carry more or deliver the products faster, which implies fuel efficiency. Thus, as a complement to the massive reduction in transportation loading due to on demand manufacturing business models, this energy efficiency promises remarkable upside in AM utilization. This lighter material is also related to social aspect of sustainability where personnel safety is a critical concern, and with lighter materials the problems that for example, company no.11 mentioned with regards to some heavy parts and installation, can be addressed.

Via embracing AM more and more, the industry can make sure that their approach is a systematic approach toward optimization and positive contribution toward the sustainability, instead of isolated effective or even ineffective sustainability approaches of individual companies and making sure their approach is result-oriented.

Social aspect

With regards to the social aspect of spare parts management by utilization of AM and DI, the most interesting point among the responses is how participants see that this approach toward DI and on demand manufacturing can affect community involvement. Due to the highly engineering and technical background of participants, in several cases the term social aspect of sustainability were explained in more detail and with examples to clarify the interpretation of the word "social".

The recurring subjects mentioned by the participants were local value creation, building knowledge locally, new job opportunities, and maintaining the population in remote locations across the long coast of Norway and near O&G platforms.

The respondents believe that this attribute of AM technology that made a single machine capable enough to produce end parts, has brought the opportunity to promote on demand manufacturing close to the end users, thus, a positive step into distributed (decentralized) manufacturing which can increase the resilience of the supply chain and based on participants with higher experience, it can contribute to more democratization of the manufacturing and the supply network.

Also, the subjects of local value creation along with building knowledge locally and new job opportunities are very important and yet interconnected, because for example, Company no. 6 (AM supplier) described that they have already communicated with the students from NTNU and students from high school locally, where they introduced the technology and familiarize students with their highly technological capabilities as well as building knowledge locally to expand their activities. This has also resulted that they expressed that the need for competent engineers in this field is growing and new job opportunities within the field of AM will be more and more in demand in the future, which is a same observation by the majority of the participants.

In this regard, participants were asked to describe whether they believe that these positions will lead into curation of new departments within their organization or merging of departments and around 70% of respondents believe that no specific change will happen regarding the departments, however, new roles can be defined, and they would work mainly within the same production, mechanical or asset management departments.

The majority of the participants mentioned about a company called, AM North that has advanced AM technology and is located in Hammerfest, northern city of Norway, and how this kind of initiatives can flourish in Norway and can significantly contribute to local value creation and maintaining the population in remote locations as well as educating young people with advanced technologies to be able to solve industrial challenges and keep the wheels of Norwegian industry rolling faster and better in the future.

Knowledge status with regards to AM

Service Providers and AM Suppliers, all believed that the level of understanding and knowledge about AM and DI in the industry, with the scale of 0 to 5, is between 2 and 3, which make a situation that can effectively hinder the AM utilization speed and its associated benefits. Thus, proper consensus and systematic set of attention and efforts in this regard is necessary to address the issue.

Around half of the participants believe that this lack of knowledge can be mostly seen from OEMs and the other half believe that this lack of knowledge has to do with the Operators.

Several participants expressed that the level of knowledge and competence can be different between the companies and the people, however, the majority of participants with higher experience believed that it is not enough that only a few people in large operators or in OEMs know so much about AM and DI, and the related knowledge should be scaled up to form a new industrial culture in order to subsequently scale the utilization of AM.

The participants were asked about their opinions with regards to whether any of these DI formations could lead to more sustainable outcomes in the industry.

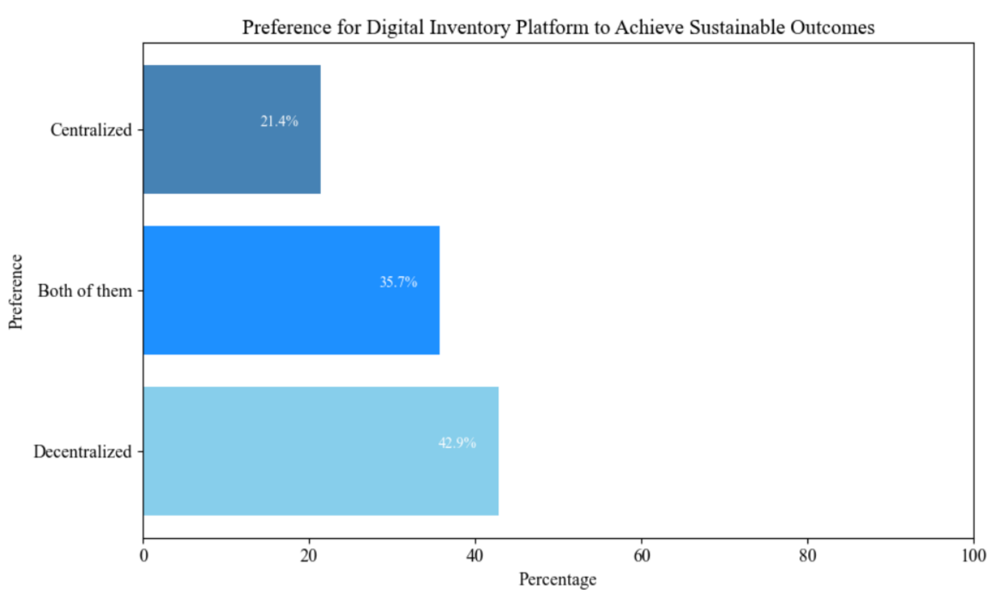

Figure 16-– Preference for DI formation – Achieving sustainable outcomes

Transparency and efficiency,

Mainly operators believed that centralized DI could bring the possibility of bringing the possibility of focusing on few 3D printing facilities and thus being able to optimize the orders and transportation and give the operators to focus on certain 3D printing facilities and thus making the operations clearer and more transparent and efficient for involved parties.

Company no. 14, expressed that with decentralized DI, they will be able to do their own calculation, more accurately report on what they believe is important for their business, instead of providing some information to centralized one that does not allow that much flexibility at their end.

Insufficient performance data of different DI formations,

All companies that expressed both of the DI formations can bring sustainable outcomes, they believed that the maturity of the technology and the utilization of these platforms are still in infancy stage and there is not enough performance data to say whether any of them may bring more sustainable outcomes.

Risk of DI platform shutdown or bankruptcy,

Companies no. 1 and 12, mentioned the main benefit for the end users is that they don't need a physical inventory, however, if their digital spare parts are included in a centralized platform and that platform shutdowns or bankrupts the operators are likely to face great risks. However, no operator representative mentioned about this risk.

Senior insights

Participants with higher range of experience here, described different factors in favor of Decentralized DI formation which will be reflected as below.

Company no. 6, believed that more freedom for change in spare parts' design specifications and enable material mix solutions that can be triggered by a decentralized DI compared to a centralized one, which it focuses on blueprints for today's parts and solutions. The decentralized DI can potentially enhance interactions and competition leading to a more dynamic AM ecosystem in the Norwegian O&G industry.

Company no. 11 described that with smaller extent of AM production, centralized DI may have higher magnitude of impact on sustainability, however, the decentralized one could accommodate higher degree of AM utilization (production rate) and consequently more positive impacts on sustainability in the long term.

Company no. 9, believed that with decentralized formation, it might be possible to start educating people, building the competence and kind of technology center in rural areas across

Norway and that certainly creates long term value for the local people economy and facilitating new levels of AM utilization in the country.

Company no. 1, the OEM, believed that the decentralized DI platform could facilitate more sustainable outcomes as it more readily allows for local production of parts, enabling quick delivery and a reduced carbon footprint. Moreover, the representative gave an example that if their service personnel in Texas need a part, a local supplier could produce and deliver it swiftly, avoiding the week-long shipping delay. This approach can simultaneously support quality control, reduces transportation emissions, which can have efficient, cost-effective outcomes and contribute to the sustainability aspect of spare parts management.

6- Discussion

This chapter focuses on presenting the findings and discussing the characteristics of the influence of digital inventory and on demand manufacturing business models on sustainable spare parts management. According to the thesis objectives, the connection between topics tried to be smooth, and break silos and draw a transparent picture of the multifaceted and interconnected influential factors in this field. The chapter builds upon the analysis conducted from the interviews and literature review and how new technologies can be used within this context.

6-1 Spare parts management and AM

With the use of DIs operators would benefit from increased transparency regarding the frequency of their orders for particular parts, significantly, reducing the time spent searching for them in different physical inventories in various locations. As mentioned in the analysis, the current practice of sharing among operators is not optimal when different assets within a single physical inventory have different owners. This challenge underscores how DIs storing a higher proportion of operational spare parts can enhance efficiency and overall performance for operators.

The synergy between operators in identifying detailed candidates in operational spare parts categories can significantly improve spare parts management performance on the NCS. An important issue discovered in the analysis is that NORSOK standards have not yet incorporated

AM, creating a barrier to further implementation. Therefore, it is imperative for NORSOK to collaborate with ISO or EU standards to integrate AM technology characteristics, thereby supporting technological developments and innovations for a more sustainable value chain in the Norwegian O&G industry.

Another challenge is the low level of customization, which is linked to existing business models, linear approaches, and inadequate suitability analysis by operators for spare parts candidates. According to analysis results and participants' perceptions regarding spare parts customization, there is a substantial business opportunity for OEMs, both small and large, and AM suppliers as they can capitalize on this potential by producing new parts for various industries. Additionally, obsolete parts also present a significant issue for operators, as they tie up capital in physical inventories. With the aging installations on the NCS, the number of obsolete parts is increasing, raising concerns of waste management and ensuring system availability for the future.

Digital inventory business models can benefit both OEMs and operators by digitizing these obsolete parts and redefining them as sort of “archived parts.” Through licensing, operators might opt for a royalty fee scenario rather than a fixed fee for having a digital version of the obsolete part. This approach benefits OEMs by enabling faster design of new products for different industries, making their production more agile to customer demands, and generating revenue instead of maintaining production lines for old parts.

In another scenario, if an OEM ceases to exist, they could sell their digital spare parts’ rights to a DI platform or an operator, allowing for design modification on demand and entering a new era of customization for spare parts, with lower costs and more effective supply chain responses. This could also initiate new innovation cycles in the industry, enhancing the responsiveness of value chains to customer demands across various industries, both regionally and globally.

According to section 4-10 and participants responses, new technologies like A.I and deep learning for 3D design optimization and automation can have significant impacts on lead time and part quality, enabling AM suppliers to shape new digital business models around DIs and on-demand manufacturing in the Norwegian O&G industry.

AM is ideal for producing complex parts that would otherwise be expensive and require many assembly parts with conventional manufacturing. AM allows designers to incorporate several functions by manufacturing a single part. As mentioned by Company no. 9, this simplifies the supply chain for capital spare parts by reducing the complexity of managing relationships with many conventionally-manufactured-part suppliers and echelons.

These business opportunities can significantly improve spare parts management efficiency and effectiveness, improving maintenance engineers' demand forecasting abilities for maximum asset availability, performance, and overall system efficiency.

Suitability analysis for spare parts based on NORSOK Z-008 categories

According to the literature, spare parts management primarily involves part classification, demand forecasting, inventory management, and performance assessment. Digital business models now provide new "exchange service processes" that will transform these steps. The literature review on SKUs of different categories of spare parts in a typical oil platform on the NCS (see section 4-3) shows that the most value-driven category is capital spare parts, despite their limited numbers. These parts have long lead times, critical for plant availability, and are expensive.

Conversely, a large proportion of parts are operational spare parts, critical for safety and system operability, contributing to almost 50% of physical inventories. Consumables account for around 6% of physical inventories, having less impact on operations and being easily accessible and inexpensive compared to the other two categories.

It can be assumed that capital and operational spare parts' designs are more complex than those of consumables, making them more critical in case of shortages. Thus, based on the number of items, in order, operational, consumable, and capital parts are the most suitable candidates for digital spares in DIs. However, if the business case focuses on availability rather than reducing inventory load, the order should be capital, operational, and consumables.

Comparing this interpretation with the analysis results, participants prioritize selecting parts that can be streamlined for easier production, are less safety-critical, and are less expensive to establish more trust between key stakeholders, such as OEMs, operators, and AM suppliers. Consequently, operational and consumable parts are the most suitable candidates. Two main challenges for DIs are the data security and existing OEM business models, as OEMs are still hesitant to engage effectively in DI platforms to provide more digital spare parts. Therefore, it is essential not to decide merely on the capital spares without specifying the exact spare part description that is to be stored in a DI and printed.

Based on comparing the analysis results and the literature review, operational spare parts are the best candidates for printing and storage in DIs. They can significantly reduce the number of spare parts in physical inventories, increase system availability, and facilitate faster and easier demand forecasting. For example, in emergencies, printing spare parts is quicker than ordering them. As elaborated in the analysis, the cost of manufacturing parts with AM would be offset by immediate delivery, with qualified AM parts potentially equal or superior in quality to conventionally manufactured parts.

6-2 Digital inventory and on demand manufacturing business models

Key characteristics for DI platforms, such as multi-sided nature, network effects, interconnectivity, and data-driven insights, are validated by the analysis results. Therefore, it circles back to the basic definition of digital business in section 4-5, in a sense that DI platforms as digital businesses aid connection and collaboration between industry partners by having an online platform to promote the new digitalized management of spare parts and subsequent manufacturing of them.

DI platforms initiates and facilitates the support, transaction, and maintenance of “service exchange processes” between different stakeholders in the AM ecosystem such as OEMs, AM suppliers, operators, technology-driven service providers, standardization companies and testing facilities and etc. through an operational digital hub. Thus, the DI platform essentially do the handling of digital spare parts, corresponding to digital manufacturing characteristic of AM, to facilitate on demand manufacturing.

Since digital spare parts are essentially product design files, ensuring their safe transfer over the internet is crucial. These files represent the core assets of OEMs, and effective AM business models must guarantee their profitability and based on the analysis result, there is a consensus that licensing for spare parts can be a great opportunity which can be facilitated by DI platforms.

DI business models

Interestingly, according to (Estarrona et al., 2019), two key trends affecting the asset management in the industry are circular economy and servitization concepts, which they argued that servitization of manufacturing industry is aligned with circular economy principles and can lead to further sustainable outcomes.

DI platforms and associated business models, as it was mentioned in the theoretical background and approved by the analysis results, is essentially stimulating a significant transition toward digital manufacturing based on AM. Therefore, these platforms force the transition from mass production of OEMs and just-in-case approach of operators into printing spare parts on demand and just-in-time close to the operators. In this way, the OEM provides the digital spare parts, either from their own digital inventory (decentralized formation) or share it with a centralized DI platform.

Consequently, an interesting finding here from consolidation of data from the literature review and the analysis chapter section 5-2-2, is that the OEMs will be selling the function of making the spare parts digitally available for on demand printing instead of creating the physical parts by themselves, which is aligned with the concept of manufacturing servitization. Linking DIs to the business model framework discussed in section 4-5, it involves four key elements: parts/services, value network, value delivery, and revenue model.

Here, the focus is on the utilization of AM for spare parts management (parts/service), while the value network is associated to AM ecosystem and it will be discussed in the next section on how different DI platforms’ formation (centralized or decentralized) can have different impacts on the adoption of AM in the manufacturing value network, particularly within the context of Norwegian O&G industry.

The value delivery is also driven by DI platforms' characteristics and the strategic benefits identified based on interviewees' opinions. Moreover, according to the digital nature of product drawing files, and to protect the OEMs' IPR, have a safe and reliable procurement processes is critical that based on the literature and analysis chapter results, licensing could be a promising option to address OEMs' revenue model.

DI business models influence on spare parts management

To fully utilize DI platforms for spare parts management, it is essential to understand their impact on four key components: part classification, demand forecasting, inventory management, and performance assessment, as detailed in section 4-3. Enhanced classification and demand forecasting capabilities can lead to more precise inventory management and improved performance assessment, ultimately driving greater efficiency and reliability in the supply chain.

Moreover, regarding part classification and demand forecasting for spare parts here is a detailed overview of the results. According to the previous section, operational spare parts (based on the NORSOK Z-008 category) are the most suitable candidates. Additionally, with the capabilities of AM, the suitability analysis for relevant candidates will be enhanced in the future to include a larger number of parts and materials.

It will also help with demand forecasting as DI platforms can, for example, provide similar services of Product lifecycle management (PLM) systems, to store the historical data for spare parts' breakdowns or operating conditions, improving the clarity and interconnectedness data across assets despite being geographically dispersed. Incorporating effective usage of spare parts' data, could contribute to the operators' maintenance team planning to have a better overview of critical spare parts' failure rates and materials for more effective and efficient preventive maintenance operations, facilitating predictive maintenance to plan accordingly, maintaining the availability of systems and ultimately expand the lifecycle of those spare parts.

Interestingly, (Wirtz, 2021), mentioned several characteristics for digital platforms such as pooling and profiling, where in the current DI platforms context, DIs can store and integrate the relevant spare parts' data centrally (pooling) and enabling the profiling for them; for example, creating specific profile for certain spare parts including information on their criticality level of with accordance to DNV-ST-B202 standard. This in fact can contribute to reducing the processing time for spare parts evaluation and verification, and thus increase the efficiency and reliability of the organizational processes within SPIR context.

Additionally, a key strategic advantage of DI platforms mentioned in the theoretical background as well as approved by the interviewees is how these platforms can contribute to commercialization of digital spare parts and empowering the AM market to facilitate large scale adoption of AM and on demand manufacturing in the Norwegian O&G industry.

These platforms provide the opportunity for enhanced coordination and direct collaboration between the key stakeholders and make the critical information such as qualification information for available parts, eventually creating a collaborative atmosphere to share relevant manufacturing detail of spare parts. This space would be able to connect the diverse requirements of stakeholders, address the IP concerns of OEMs effectively and make the expectations of operators more aligned, contributing to a dynamic and productive AM ecosystem.

On the contrary, according to the participants' perspective about the key challenges of utilization of DIs, the discussed themes were including current AM-market structure, the incompatibility of organizations' digital infrastructure to communicate digitally with DI platforms, OEMs' concerns about the IPR of their digital spare parts and developing suitable commercial and tailor-made models between the key stakeholders, such as OEMs, AM suppliers and operators. Moreover, a considerable challenge mentioned by operators is how to include the provision of digital spare parts within the existing contracts with the OEMs and vendors.

The use of DI platforms can also bring an incentive for OEMs by avoiding buybacks of unused parts from customers who operate with Buy-back policies and, therefore, cutting the financial liability associated with unsold inventory. Additionally, DI platforms mainly benefit the operators in two ways: they minimize up-front costs, usually incurred with the just-in-case approach, and reduce physical inventory, especially of obsolete parts, thus improving operational efficiency.

From an asset management point of view, the primary Capex benefit for OEMs comes from avoiding the financial burden of buybacks and reducing the need for large-scale production of parts. For operators, the key advantage is avoiding the large batch purchasing and capital lock of spare parts in the physical inventories, contributing to better capital allocation planning and furthermore, repurposing the existing inventories' space and also reducing Opex through enhanced operational efficiency and reduced storage and handling costs.

With regards to the inventory management aspect of the spare parts management, the DI platforms policies are affected similarly by the influencing factors for inventory management policies, described in section 4-2, such as system structure, market characteristics, parts, cost and lead time.

System structure and the value network aspects of DI platforms are discussed in more detail in the next section. Regarding the market characteristics, also according to chapter three, Contextual background, it becomes clear that primary goal for operators regarding spare parts management is to maintain the availability of the systems, reducing lead time and make the processes more agile and efficient as well as considering the sustainability aspects of these processes.

DIs and on demand manufacturing, based on what is discussed earlier, can significantly decrease the lead time for spare parts, as several examples were discussed in section 5-2-3. However, with regards to cost for the AM parts, based on the analysis chapter, section 5-2-1, the more complex the part is, the more AM method would be efficient. In addition, based on several inputs from participants with a high range of experience, the ideal parts for AM are still fairly rare and they believed those parts' design will be quite complex that may not be feasible, either economically or technologically, to be produced via other manufacturing methods, and they call such parts as "future parts".

Regarding the performance assessment aspect of spare parts management, the key criteria as emphasized in the theoretical background is the coordination level, where if not properly addressed can cause significant financial loss, damage to reputation and may severely endanger operational safety, while considering the offshore platforms, these consequences can become significantly severe.

Therefore, DI platforms can potentially have considerable impact on increased efficiency, coordination between stakeholders and service level of service providers for the complex task of spare parts management. Here, one can assume that DI platforms can act like an asset management system to integrate the data to provide in-depth and multi-level information on digital spare parts and contributing to high quality data to have informed and risk-based decision-making process. This in turn, could facilitate the spare parts interchangeability record (SPIR) and prevent missing information that regularly may lead to delays in spare parts availability for operational teams at operators' premises.

Here, Smart contracts, based on the information in section 4-10, can be implemented in these DI platforms to increase the overall value delivery among platform participants and automate a proportion of procurement processes to increase efficiency and effectiveness for spare parts management for the value network.

On demand manufacturing

Reflecting on the three critical elements of robust on-demand manufacturing outlined in section 4-8—advanced manufacturing technologies with proper capacity management, a network of certified manufacturers, and access to a dynamic market—the results are as follows.

According to the analysis chapter, it became clear that the OEMs have not shown sufficient flexibility and engagement toward AM and DI. One of the main reasons that participants highlighted is the limited manufacturing capacity of the AM suppliers in Norway. Thus, the OEMs cannot effectively move a proportion of their production capacity to AM suppliers. This capacity limitation also goes back to the limited number of certified AM suppliers in Norway, which is directly affected by the expensive and time-consuming qualification processes, as well as the lack of competence and knowledge among organizations with AM machines and other key stakeholders regarding AM qualification requirements.

However, to systematically enable scalable on-demand manufacturing in the industry, there is a need for DI platforms to establish secure and capable mechanisms to gain stakeholders' trust and thus participation to commercialize digital spare parts. However, based on the analysis results, operators do not want to approach the idea of in-house production of AM, as their core business model is not manufacturing. According to operators' representatives, if they attempt to approach such a scenario, they will most probably face knowledge challenges, as AM is a highly advanced manufacturing method. Also, ensuring the efficiency of the processes and the safety of the printed parts is not an area where they have invested or developed sufficient competence.

Based on the participants' opinions, Norwegian OEMs are more willing to cooperate and effectively engage in the adoption of new AM-based business models and working with DI platforms. Therefore, this situation can be advantageous and serve as a strong business model where proactive operators strengthen their bonds with OEMs and AM suppliers to shape strategic partnerships. These partnerships can create an exclusive value network, enabling operators to source more parts through specific AM suppliers, increasing volume and making it attractive for OEMs to shift a proportion of their production to this network.

Ultimately, it is evident that the development in AM and DI fields has gained significant momentum compared to a few years ago, when there were no solid AM standards. This progress facilitates dynamic circularity between the demands from operators and the supply from Norwegian OEMs and AM suppliers, leading to enhanced regional value creation in Norway's energy industry.

Interestingly, during the course of this thesis, in April 2024, Aker BP and Aker Solutions, as leading companies in Norway's energy sector, announced that they are launching an AM facility with collaboration of an AM supplier in Stord Yard, to harvest on capabilities of on demand manufacturing to increase their responsiveness toward their operational needs and thus, increase their on-site productivity. (Solutions, 2024)

Qualification

Based on the analysis results, there is a clear correlation between the capacity of AM suppliers and the utilization of DI platforms. AM suppliers must be available to receive and manufacture digital spare parts. A primary concern for operators is the qualification process which is mentioned by respondents as a challenging point. and technical discussions. However, entering this market poses significant investment barriers due to the funding required for qualification and the time-consuming process, which can take around a year. This results in investment risks and demand uncertainty due to insufficient orders from end users.

This is the consequence of lack of demands in the market, covered in section 5-2-2, that market structure for AM demand, currently is only leading by Equinor, which makes Equinor a single buyer in the market, and thus, AM suppliers see the market uncertainty high as the demand is still very limited and the power on the buyer side is mainly based on one actor.

Another factor that complicates the situation is the operators' lack of capacity for suitability analysis of parts to be printed, as revealed in the analysis chapter. Although operators may have a good awareness about AM benefits, the majority of participants believed that they are not taking effective steps towards implementation. Participants suggested that operators need to rethink their strategies, adapt their strategies to a result-oriented sustainable strategies, instead of sticking to a just-in-case approach and only buying new parts when needed. Commitment from operators to show interest and embrace available technological advancements and tools to utilize AM to address sustainability issues is a win-win strategy for all the stakeholders toward reshaping the industry into a more interconnected and resilient way, which requires efforts from the key stakeholders to address the culture change in an integrated way and actively promotes AM as a reliable new manufacturing method, promising for mass customization and material consumption efficiency as well as more simplified supply chain.

Additionally, operators should focus on increasing their knowledge and capacity for suitability analysis to better identify parts that can be effectively printed. This approach will help drive demand for AM suppliers, reduce investment risks for qualification process, and foster a more robust market for DI platforms.

The analysis also highlights that the poor level of suitability analysis for spare parts is also tied to the lack of specific key acceptance criteria for materials in current standards. By the way, with the standardization development plans by DNV, this issue can be addressed and other standards like NORSOK Z-008 must also incorporate such criteria regarding AM to facilitate the adoption of AM and its sustainable outcomes for spare parts management in the Norwegian O&G industry.

Another key challenge mentioned for on-demand manufacturing, both in the literature and confirmed by participants is the distance of AM facilities to test centers to qualify the final product if the parts are critical according to DNV-ST-B203. Thus, as mentioned in section 4-8, a hub configuration can address this issue by selecting certain zones and building up facilities there, preventing from centralizing all facilities in one place or complete decentralization of them.

A technological solution for this issue, based on section 4-10, is that the AM suppliers and testing facility centers implement and invest on Digital Twins technology, where the quality of the final products can be estimated via advanced simulation tools and thus a remote monitoring can enable the testing facility centers as well as AM suppliers benefit from reducing transshipment and high mobilization costs, needless to say, the operators receive qualified parts as soon as possible. A relevant idea to this point is an example that Company no. 6 described, that for repairing noncritical parts they need two weeks, and for critical parts another two weeks will be added. Therefore, implementation of Digital Twins technology can be a promising and complementary tool to further decrease the lead time, while adhering to strict qualification processes.

Also, almost all participants believe that regional transportation may increase with the adoption of on demand manufacturing. This suggests that while local transportation and mobilization costs may not see significant reductions, the transportation costs from abroad can be considerably experience reduction, as it is aligned with the characteristics discussed for AM and on demand manufacturing.

Licensing

As it was discussed earlier about the promising feature of licensing for digital spare parts, it can facilitate the AM industrialization and also add value to DI platforms. Based on the literature and the analysis, licensing for spare parts is a promising opportunity for the stakeholders to harvest on it and develop new tailor-made commercial models based on different parties' interests and requirements, being it OEMs, operators, AM suppliers, service providers etc.

Two key characteristics that were mentioned in the literature about licensing for digital spare parts are related to fixed fee and royalty fee, and these were discussed extensively with the participants, and the reflected opinions can be reviewed in section, 5-2-3.

It was elaborated by almost all participants that the combination of fixed fee and royalty fee are the best available option to start the adoption of licensing for digital spare parts within the context of the Norwegian O&G industry. Drawing conclusion from the aforementioned section in the analysis chapter, licensing could be very beneficial in financially supporting the AM suppliers as this approach can stabilize their revenue model to overcome the high upfront cost for certification.

There, it was revealed two other parameters based on participants' responses for licensing of digital spare parts which are the durability of printed parts as well as the liability subjects and corresponding cash flow management of the involved parties to maximize their gains.

While based on the literature, licensing can significantly increase the profitability of OEMs, the gains of the buyers were not elaborated on sufficiently. Here, based on the analysis chapter, it can be interpreted that licensing for large number of spare parts can also be challenging for operators and this approach must be handled via multi-disciplinary teams to collaborate and evaluate thoroughly the terms and conditions of licensing, its corresponding part description, durability and other important factors like criticality.

However, an interesting long-term idea is that licensing for digital spare parts could ensure that the higher the quality of the part design and the end product, based on the complexity of the part, the greater the financial gain for OEMs. This also increases the overall reliability of the operator’s systems, especially for critical equipment. Thus, it could potentially start a trend where AM parts compete more extensively with CM parts, particularly for advanced applications that require enhanced durability and longer lifecycles.

Another possible and interesting business model, based on participants' opinions, is that companies not necessarily being OEMs but possessing digital files for obsolete parts can enter the market. These companies can provide their design files and earn revenue, for example, through a fixed fee.

Presumably, one of the reasons that is relevant when the OEM expression is used is that because in the physically oriented supply chain including of many geographically distributed echelons, it helped to understand the originality of a part and clarify the traceability and visibility. This issue can also be digitalized where the originality and credibility of designers and designs might become a concern and DI platforms can be extremely helpful in qualifying them and contribute to a reliable, safe, traceable and robust digital value network.

Interestingly, AM and DIs can open up doors for a new industrial language where, in the coming years, terms like “original equipment designers”, may emerge and taking a share of the AM market. This sort of digital developments are crucial to be considered and planned for by all stakeholders as they can profoundly impact the manufacturing industry, whether within a specific sector like the Norwegian O&G industry or on a regional and global scale. This could also lead to a paradigm shift that can empower the digital supply network more than ever before. Therefore, OEMs, in particular, must anticipate and plan for such scenarios in order to maintain their competitive advantage by embracing new technologies, invest in new digital capabilities and adapt to new performance requirements in the value network.

Moreover, based on the literature, section 4-8, it was anticipated by (Y. Zhang et al., 2022), that with the relatively equal price of AM and CM parts, the adoption of licensing for digital spare parts would become significant among OEMs. This relatively equal price, expressed by several interviewed AM suppliers, is achievable based on their technological capabilities and corporate strategies.

Thus, according to literature and experts’ opinions, it appears that although the momentum for adopting licensing is not currently high, particularly within the Norwegian O&G industry, an era of competition for licensing digital spare parts is imminent. Apparently, proactive OEMs and ambitious operators in the sector can benefit from these conditions before the real competition begins.

Environmental and social aspects of Sustainability

As mentioned in section 4-9, improving an organization's business performance requires a deep understanding of several factors, such as competitive forces in the global industry, new business environments, and the alignment of business models with future needs.

DI platforms can facilitate on-demand manufacturing and customized spare parts production, as per to the evolving operational requirements of operators, which may result in further innovation and sustainable solutions. Thus, DI platforms and on-demand manufacturing business models can facilitate the transition from mass production to mass customization, enabling OEMs to diversify their products between AM and CM based on various factors. As discussed in the analysis chapter, AM allows for a level of customization where designers can optimize part performance while ensuring the final product meets qualification requirements. This can lead to operational energy efficiency, as elaborated in section 5-2-4.

Moreover, reducing the weight of parts—one of the capabilities of AM technology—can improve safety for personnel working offshore or onshore to install different equipment, and thus contribute to the social aspect of sustainability. Also, this can particularly address the Reduce pillar of circular economy, that by implementing AM to produce parts that consume less material while providing the same functionality as conventionally manufactured parts, it can significantly reduce the need for virgin materials.

Based on interviewees' opinions, repair services could become a key offering of DI platforms. These platforms can facilitate design modifications through more collaborative and effective digital hubs that can connect key stakeholders to increase coordination and remove different operational obstacles. These platforms can also organize AM repair services on a larger scale, improving data integrity for assets and profiling spare parts. By focusing on repair, there is a clear contribution to circular economy, that by Reducing the need to purchase new parts, it will result in extracting fewer raw materials, and reusing spare parts. This is particularly supported by AM Suppliers' opinions in section 5-2-4 and emphasized by (Le et al., 2015) who noted that "opportunities exist to increase efficiency and create value through the use of 3DP for end-of-life parts, generating reuse cycles for worn-out components."

Furthermore, the large number of obsolete parts in operators' physical inventories, particularly as assets reach the end of their lifecycle, presents an opportunity to digitize these parts through 3D scanning and then recycle them. The recycled material, as mentioned in the literature and approved by participants, can be used as feedstock for AM, thus supporting the Recycle pillar of circular economy.

Currently, repair and maintenance services in DI platforms are not available, but participants welcomed the idea of incorporating such services. They noted that it also depends on whether the repair is conducted on-site or at an AM facility. This approach could particularly enhance the sustainability of spare parts management for the Norwegian O&G industry. However, participants with extensive experience emphasized the need for a "culture change".

Relevant to this idea, participants suggested that DI platforms, besides providing information and facilitating coordination among key stakeholders, could also offer relevant knowledge within AM, thereby increasing the overall knowledge level of stakeholders, i.e. educating the platform participants about the updates or requirements in the AM field.

Regarding the social aspect of sustainability, it was strongly emphasized by the participants that utilization of DIs can have positive impacts on community involvement. This can in turn, can contribute to regional value creation in remote parts of Norway, for example, in northern Norway, which can have several considerable benefits such as educating the young people about advanced technologies like AM, creating sustainable job opportunities which can furthermore maintain the population in rural areas and contribute to further local development and resilience.

Drawing inferences from the interviewees' opinions, a critical factor to be addressed is the increasing knowledge about AM capabilities, which makes gaining broad acceptance for AM utilization in the industry more accessible. Although the industrialization of AM is still in its early stages and the on-demand manufacturing of spare parts for the Norwegian O&G industry is currently limited, the interviewees believe that with the proper development of DI platforms, an increase in the number of AM suppliers, and higher competence among key stakeholders in adhering to AM standards, significant growth in the AM market can be expected in the coming years. This growth will also address the sustainability concerns of the Norwegian O&G industry.

Therefore, organizations operating on the NCS must rethink their strategies toward AM and DI to maintain their competitiveness. For sustainable development, financial strength cannot solely be the source of future success for organizations as new shaping factors in regional and global economy asks for implementing certain measures for addressing different aspects of sustainability.

Lastly, implementation of Digital Product Passport (DPP) within the DI platforms can have several important contributions toward a sustainable value network within the context of Norwegian O&G industry. As it was mentioned in section 4-10, this service would enable the customers to gain information about the part original supplier and their production processes, as well as verification of the origin and quality of materials used. For example, different platforms can enforce DNV standards, and then if the parts meet specific criteria, they can be registered DI platforms. This ensures a higher level of visibility, responsibility toward quality and enabling the stakeholders to make informed decisions.

6-3 Governance for Digital inventory platforms

The relevance of centralized and decentralized digital inventory platforms to digital business models, especially industrial digital platforms, is significant and multifaceted. Digital platforms facilitate “service exchange processes” between consumers and producers, leveraging digital inventory systems to optimize operations, enhance user experiences, and create value.

Key points from (Pauli et al., 2021), highlight two building blocks of digital industrial platforms: data collection/analysis from industrial assets and streamlining data-driven applications among industrial actors. In the Norwegian O&G industry, DI platform development relies on key stakeholders' participation, reflecting a B2B interaction with complex decision-making processes.

Furthermore, digital platforms act as digital marketplaces, intermediaries that centralize data to facilitate transaction transparency, enhance data accessibility, and extend organizational reach, fostering a dynamic ecosystem. Decentralization level also critically influences platforms' core business models and digital spare parts management. According to (Chen et al., 2021), effective governance, driven by participation levels of suppliers and customers, is vital for robust service provision. Thus, key governance parameters include individual incentives and local information to ensure desirable participation rates.

Digital inventory platforms must address these parameters to achieve high participation rates and gain a competitive edge. Here, the focus is on the functional role of digital inventories in facilitating digital spare parts processes and eventually enabling on-demand manufacturing. A comparison between literature and participant opinions identifies similarities and new factors in addressing the Norwegian O&G industry's needs and characteristics.

Basically, the idea of centralized digital inventory platform revolves around the aim to make the digital spare parts available for operators to print the spare parts on demand by storing the digital spare parts, provided by OEMs in itself.

On the contrast, the decentralized digital inventory platform, aims not to store digital spare parts in itself, but building up a platform that decentralized digital inventories owned by OEMs or other actors, can be connected to the platform and present the availability of their digital spare parts for buyers.

In other words, centralized digital inventory platform provides actual availability, by storing the OEM’s owned files in itself, while decentralized form, only present the availability of the parts, thus, OEM’s have more control over their IP and digital spare parts.

However, the level of decentralization and platform policies are crucial for achieving higher participation rates and fostering continuous improvements. It is also important to mention that two major DIs are operating currently in the Norwegian O&G industry and facilitate the digital spare parts management processes, in which, their business models are more aligned with centralized formation, and there is still no major platform that presents the characteristics of the decentralized digital inventory formation.

Centralized formation

Based on the analysis section, the centralized digital inventory platform formation, provides an opportunity for consolidation data and increase the collaboration between the stakeholders, while keeping the data sharing personalized to the users, as it was described an advantage of this formation.

This formation is also able to ensure the global standards to prevent the diversification of standards and thus reducing the technical discussions, as it was mentioned a challenge for AM suppliers, and it can also be helpful to uniform the operators' expectations and facilitate the overall qualification process for spare parts.

However, with regards to enabling a cluster of 3D manufacturing in the Norwegian O&G industry, participants mainly believed that this formation is insufficient to do so, as its reachability is limited to certain number of suppliers and with regards to platform subscription fees, this might be a barrier for new entries and raise overall costs for the stakeholders.

With regards to sustainability, based on the participants' opinion the centralized formation is also not able to address the sustainability concerns solely, despite its focus on limited range of participants, aligned with the consensus that in the future there will be more of AM suppliers with bigger capacities in Norway and stronger demand for on demand manufacturing, the centralized have inherent limitations in scalability and balancing the demands and solutions as they eventually will need a central controller to approve them and potentially can limit the innovation in this field, limiting the contribution of AM technology toward sustainability.

Therefore, drawing conclusions from the theoretical background and the analysis sections, the key challenges with regards to individual incentives include, first, balancing control with stakeholders' demands and solutions, and secondly, as persistently mentioned by respondents, ensuring fair and transparent incentive distribution.

Moreover, risk of unavailability of digital spare parts, either critical or obsolete, either temporarily (cyberattacks or other technical issues) or permanently (platform bankruptcy or shutdown) is challenging point when it comes to local information and centralization of digital spare parts.

The opportunities of centralized DI formation are numerous when comparing the literature review of platform governance characteristics and the DI platform preference of respondents. Such opportunities relevance to individual incentives include, streamlined operations and clear accountability and a potential for strong leadership that can enforce unified goals. However, this in fact is a complex concept that requires further studies on clarifying the benefits and drawbacks of the DI platform. Also, being relevant to local information, improved data-driven decision-making at the central level and easier to implement global standards and practices are the key opportunities that would enable the participants to interact seamlessly and effectively with the platform services.

Decentralized formation

Based on the analysis chapter, considering that decentralized DIs enabling the OEMs to have more control over their digital parts, as they have their digital part in their own digital inventory that is connected to the decentralized digital inventory platform. Thus, it can address the OEMs' priority about having revision control and reducing the risk of sharing their product designs in several other platforms. It can be also a better risk-based approach for operators to use a decentralized platform that eliminates the inherent risk of unavailability of the parts due to platform shutdown or bankruptcy.

Moreover, it can potentially lead to platforms that show the digital parts without showing the functionality of them. This is an interesting view, because in this way the OEMs could put their parts and use the DI platform as a marketing tool as the parts are searchable and observable, but the part functionality information are hidden to essentially protect intellectual property of OEMs. The trust between stakeholders and how the platforms could establish and maintain trust through designing robust mechanisms are the key parameters here for efficient, secure and reliable processes.

With decentralized formation, as it was elaborated by the interviewees, orchestrating and coordination between the stakeholders might be more difficult than the centralized formation. For example, regarding qualifications, different stakeholders may follow different standards for different parts and thus, coordination may face lack of agility. However, the knowledge and competence level of stakeholders have direct influence on whether this decentralization of decision making can be beneficial or act as an obstacle for further AM utilization.

It was also expressed that because decentralized digital inventory formation is more aligned with the distributed manufacturing characteristic of AM, therefore, it might decrease the delivery time of printed parts and increase the local value creation. This is also in line with sustainability, as despite the overall efficiency may be affected by decentralized manufacturing, however, considering the bigger picture of how broad AM utilization can contribute to enable new businesses locally, significantly decreasing lead times, contribute to physical inventory reductions and increase the availability and maintenance planning, thus, in the long term the decentralized formation may be able to support distributed manufacturing and nurture new innovative business models locally across Norway.

With regards to cluster of 3D manufacturing, it was expressed that robust solutions are derived from more options and more options can be accessed via decentralized formation in a more cost-efficient way. However, a valid and important concern raised here as the quality and credibility control of the solutions provided by decentralized entities/units participating in the platform is necessary then to truly and securely be able to address the requirements from stakeholders.

Therefore, drawing conclusions from the theoretical background and the analysis sections, the challenges and opportunities of a decentralized DI platform with regards to individual incentives include managing diverse and potentially conflicting incentives and also ensuring consistent application of incentive policies across decentralized units. These challenges are also closely linked to local information challenges, such as maintaining data consistency and integrity across the decentralized DIs.

Nevertheless, the opportunities of this DI formation is also considerable as, emphasized by respondents, these platforms can facilitate innovation, adaptability and modification enhancement among the key stakeholders. Additionally, contributing to greater satisfaction and motivation among stakeholders through tailored incentives. The aforementioned opportunities are related to individual incentives and for local information, reliance on local problem-solving instead of central control and approval, is a great advantage to encourage for innovative solutions and flourishing the AM ecosystem within the context of the Norwegian O&G industry.

Coexistence of both formations

It was revealed in the analysis that AM suppliers, emphasized that based on customers' demand variation, both of the formation must work in parallel in order to have a robust and reliable and innovative AM ecosystem in Norway not only for the O&G industry but to be more configurable and contribute to other industries like defense industry, aerospace, and aquaculture industry. Interestingly, for aquaculture industry, as one of the future promising industries in Norway, the digital inventory platforms can be very useful to enable on demand manufacturing of plastic parts to ensure safe operations and ensure safe and reliable operations to maintain the healthiness level of the fish.

Service providers mostly agreed with the decentralized DI formation as a properly designed platform can potentially increase the order level and increase the momentum in the AM ecosystem in the Norwegian O&G industry. However, they believe both of these formations will coexist in the future and with gradual maturity of AM technology, better establishment of standards and qualification processes, the applicability of the DI platforms to respond to various needs and purposes will become more clear.

With regards to qualification, based on the analysis section, it appears that both of the formations are able to facilitate the qualification process. Also, with regards to new DNV's service of on demand qualification, it was expressed during the interviews that DNV aims to encourage a multiplatform ecosystem and as long as DNV's quality-of-service criteria for DI platforms are sufficiently met, they can cooperate with these platforms to integrate their services and thus, making the processes more cost efficient and increasing trust as a key value in the platforms.

Influencing factors for DI governance

The choice between centralized and decentralized governance for DI platforms involves balancing individual incentives and local information. Centralized systems ensure consistency and control but may lack flexibility and scalability in the long term. Decentralized systems offer customization and resilience but could struggle with large-scale coordination between participants and more complex processes on data integration quality.

In the Norwegian O&G industry, the decision should align with strategic goals, stakeholder needs, and digital infrastructure maturity. A hybrid approach that both systems coexist could also balance the strengths of both systems, maximizing benefits while mitigating challenges.

In addition, by placing a weight on Senior insights, it appears that the decentralized formation has a higher probability in enhancing the utilization of AM in larger scale than what centralized formation can offer within the context of the Norwegian O&G industry.

Thus, with guidance from literature about digital platforms governance and analyzing it with the participants' opinions about the DI platforms governance, the key conditions for preferred DI formations are related to these factors,

- OEM participation: Participation of OEMs is vital for the success of DI platforms as it ensures the availability of original spare parts and technical support for possible modifications and further revision control. Also, according to the analysis chapter, knowledge level of stakeholders can directly impact their preference for DI platform formation.

- Risk Concentration: According to the literature and analysis results, centralized governance poses a higher risk concentration, as it stores digital spare parts centrally which could lead to significant vulnerabilities for both OEMs and operators.

- Transparency and Collaboration: Both centralized and decentralized DI formations can contribute to transparent collaboration. While, centralized DI formation can streamline operations and provide clear accountability by having effective central control, decentralized governance can also enhance innovation and customizations as the processes are managed by each stakeholder which generally can lead to higher stakeholders' satisfaction and thus, higher participation and development rate (network effects)

- Cost Sharing – economy of scale: As mentioned by several participants, centralized formation can potentially achieve economies of scale, for example reducing costs regarding qualification processes or access to advanced digital infrastructure. However, it was also mentioned that the subscription fee that currently are applied, can limit the participation rate, and thus neutralize the possible benefits of cost sharing.

- Flexibility and local decision making: the decentralized formation has inherent flexibility that it can contribute to higher level of adaptability to market trends, allowing for tailored incentives and innovative solutions from various service providers.
  This is also relevant to the production capacity for AM suppliers. As the demand for AM spare parts grows, decentralized formations might become more suitable due to their ability to handle diverse and increased production and operators' requirements. Decentralized formation can better address this as it will enable AM suppliers to timely and efficiently respond to demands.

7- Conclusion

In this chapter, the thesis objectives and the research question, described in the introduction chapter, are addressed based on the insights from the previous chapters, along with a discussion of the limitations of this thesis and suggestions for further work.

The offering of DI promotes on demand manufacturing, in which it aims to reduce the overstock in the physical inventories, which incorporated with many direct and indirect costs, and also ensuring the asset owners for better planning for their maintenance activities as they can print the part they want on demand and cancelling the long lead times.

According to Senior Insights-1 in section 5-2-2, working with DIs will become a necessity for organizations in the near future. Thus, proactive actors have to prepare their strategies on how to align their core assets and competencies to be able to gain most benefits in the new interconnected ecosystem driven by numerous characteristics of AM technology.

Therefore, participating in DI platforms would allow a new way of value creation, which is essentially incorporating advanced and agile digital tools in the manufacturing ecosystem and provide an opportunity to make the Norwegian O&G industry as a globally leading shelf in adapting to new technologies and addressing sustainability concerns in a systematic and effective manner. This transition would make the sector more attractive for further investments and technological developments, enhanced local value creation and maintain sector's contribution to Norway's economy.

Here, a brief review of the key findings related to the thesis objectives is provided to conclude the thesis.

Objectives:

- Current spare parts management challenges and the suitability of spare parts based on NORSOK Z-008 for AM

It has been confirmed that obsolete parts contribute to the large inventories and tie up capital in physical inventories, and with regards to new production licenses for Norwegian O&G companies, the need for spare parts is growing and with regards to aging installations on NCS, waste management concerns got importance more than ever and with new technologies the parts from the decommissioned platforms and obsolete parts can be recycled, as for example, metal powder and used as feedstock for AM to produce new parts, relevant to the recycle pillar of CE and a considerable contribution the sustainability profile of the Norwegian O&G industry.

According to section 6-1, respondents highlighted a critical point regarding the utilization of DIs to facilitate on-demand manufacturing of spare parts: the current market structure in the Norwegian O&G industry is predominantly driven by a single buyer, Equinor. Thus, it was mentioned that the demand rate for on- demand manufacturing of spare parts is very low and that has complex interactions between the certification costs for AM suppliers and their uncertainty about the future demands, the lack of operators' capacity to identify suitable spare parts for AM and requirement for more comprehensive standards to facilitate the qualification of spare parts (such as lack of key acceptance criteria for polymer parts and a need for NORSOK standards to incorporate AM.)

Thus, an analysis based on respondents' preference of suitable spare parts, based on NORSOK Z-008 category, for AM conducted and revealed that operational spare parts, and then consumables can be the best candidates as they are often smaller, used in high numbers, can be more favorably or cost efficiently produced on demand, and a very important part of it is that a large number of them also do not go under IP protection and can be produced more easily.

- Attributes of digital inventories and their value to spare parts management.

Based on the thesis findings, the DIs are essentially dependent on the AM technology as the production of end parts due to technological advancements is available that AM machines would receive digital spare parts, the digital product drawings, and then the parts can be manufactured with less material consumption, and providing the designers to achieve complex and advanced geometries that may not be economically or technologically possible for other current manufacturing methods to produce.

Thus, a considerable strategic advantage of DI platforms is that it commercialize the distribution of digital spare parts between key stakeholders such as operators, OEMs, AM suppliers, relevant regulatory bodies, testing facilities and various service providers, in a safe and organized manner.

The way that DI platforms seek to do the commercialization is aligned with digital business models that incorporate the servitization of manufacturing industry, in which with DIs, the OEMs would be selling the function of making the parts available for the need of on demand manufacturing, instead of producing the parts and delivering them through numerous echelons.

Moreover, as coordination is the key for effective and efficient spare parts management, the emergence of Digital inventory platforms, equipped with data-driven capabilities, can act as an intermediary between key stakeholders (multisided nature) be a promising digital tool (data-driven) to address the coordination (interconnection) to benefit the complex task of spare parts management in the Norwegian O&G industry.

Also a key for further development and contribution of these platforms to spare parts management and the sustainability aspect of it, is that it requires a fair number of platform participant to basically streamline the operations and enable the value creation for all involved parties, whether the operators, as they can reduce their physical inventories and all the associated costs, cancelling long lead times, reliance on foreign suppliers, reducing vulnerability to disruptions in global supply chain and increasing the industry resilience, as well as providing the

OEMs to adopt licensing and thus diversifying their revenue streams, which is in fact a great upside for them, or they will not need to buy back the remained parts, if their customers follow buy-back policies.

These strategic advantages can enhance the efficiency and effectiveness of spare parts management, including processes such as part classification, demand forecasting, inventory management and performance assessment.

- Modern conditions for on-demand manufacturing of spare parts

According to the thesis findings, three elements constitute an effective on demand manufacturing approach, which are mainly possessing advanced manufacturing methods, network of certified manufacturers, and access to a dynamic market.

    - Advanced Manufacturing Methods:

AM suppliers possess advanced technology and according to respondents' opinions and elaborated real-world examples, they demonstrate robust capabilities, making them reliable and agile problem-solvers to produce and provide spare parts for various industries such as O&G industry, aquaculture, marine industry, aerospace and etc.

    - Network of Certified Manufacturers:

In the Norwegian O&G industry, a key focus is the qualification for spare parts according to the criticality levels of the DNV-ST-B203 standard.

Strict qualification processes ensure operational safety and reliability, but the high upfront certification costs limit broader AM utilization.

This limitation affects OEMs' willingness to shift part of their production line to AM suppliers for digital spare parts manufacturing.

    - Access to a Dynamic Market:

It is confirmed by the literature and interviewees that licensing is a promising feature that facilitates AM adoption in the industry and adds value to commercialization through DIs.

Participants believed that a mix of fixed and royalty fees would be ideal for early stages of AM industrialization and added that durability of AM parts and liability issues are crucial factors in decision-making in this area.

For further detail information, please visit section 6-2.

- Opportunities and challenges of centralized and decentralized digital inventories

Here, a brief review of the key opportunities and challenges is described.

- Centralized DI Formation:

Opportunities: Centralized DIs can consolidate data centrally, enabling better data integration and streamlining coordination between platform participants. By harvesting on effective central control and strong leadership, these platforms can support unified goals, for example, enforcing adherence to specific qualification standards.

Challenges: Participation in these DIs may require specific incentive justification. There is an inherent risk for both parties in case of platform unavailability, and OEMs may face significant challenges in revision control over thousands of parts, in case of working with several alike platforms.

- Decentralized DI Formation:

Opportunities: Decentralized DI have better potential to align with open market principles, enabling adaptability to market trends and giving stakeholders higher control over their products and services. OEMs also can manage revision control effectively and reduce data leakage risks compared to centralized formation. Customization and modification processes can be handled more efficiently, ultimately contributing to a modular platform that satisfies various needs of stakeholders.

Challenges: In these platforms, large-scale coordination might be difficult, and managing data integrity and digital interfaces between stakeholders' systems can be challenging. Ensuring the credibility of platform participants is also crucial to maintaining a safe and trustworthy ecosystem.

Nevertheless, please review opportunities and challenges of DI formations in detail in an interesting discussion included in section 6-3.

- How digital inventories and on-demand manufacturing for spare parts can facilitate sustainable development in the Norwegian O&G industry

Digital inventories and on-demand manufacturing for spare parts can drive sustainable development in the Norwegian O&G industry by transitioning from mass production to mass customization. DI platforms enhance operational efficiency, reduce material consumption, and support circular economy pillars: Reduce, Reuse, and Recycle.

They facilitate design modifications, repair services, and digitization of obsolete parts, which can be recycled as feedstock for AM. Additionally, these platforms promote community involvement, regional value creation, and advanced technology adoption, contributing to both environmental and social sustainability. Organizations must embrace these strategies to maintain competitiveness and address evolving sustainability demands.

According to the thesis findings, sustainable solutions for tomorrow exist, but they are only to be developed through a stronger industry commitment, integration and collaborative effort in changing industrial culture to extensively accept AM, and thus utilization of DIs and on demand manufacturing for sustainable value creation on the NCS.

Research question:

- What are the impacts of utilizing digital inventories to facilitate on-demand manufacturing of spare parts to support the Norwegian O&G industry's approach toward sustainable value creation?

Ultimately, to conclude briefly, the utilization of DIs and on-demand manufacturing, as supported by the literature and confirmed by the comprehensive analysis of AM experts within the Norwegian O&G industry, reveals that these technologies can significantly enhance the industry's sustainable value creation by:

- Operational Efficiency: DIs could reduce physical inventories, cutting all associated costs and ensuring timely availability of spare parts, which streamlines maintenance and reduces downtime.
- Sustainability: On demand manufacturing can support circular economy principles—Reduce, Reuse, Recycle—by enabling the production of parts with less material, facilitating repair services, and recycling obsolete parts.
- Dynamic value network: The active and effective presence of both DI formations in the industry would foster higher levels of integrity, resilience, and value creation, leveraging the highly advanced AM technology.
- Qualification: DNV's exemplary role in facilitating the qualification standards for AM production ensures a safe and reliable operations in the industry.
- Licensing: Through adoption of licensing, both OEMs and operators can enjoy the benefits of their approach toward digital spare parts and on demand manufacturing. While this feature can start new innovations and strategic partnerships between the key stakeholders in the value chain
- Customization: DIs could facilitate the extensive adoption of AM to enable mass customization, allowing OEMs to produce high-quality, complex parts that meet evolving operators' operational needs.
- Regional Value Creation: Promoting local AM suppliers and creating sustainable job opportunities, thus fostering community involvement and economic growth.

Limitation and further work

A holistic and systematic approach was adopted to adequately address the various subjects reflecting the multifaceted influence of DIs and on-demand manufacturing for spare parts, as well as their sustainability aspects within the context of the Norwegian O&G industry. Additionally, it should be noted that two key delimitation areas of this thesis is the exclusion of cybersecurity-related topics for DIs and the consideration of CNC for on-demand manufacturing.

One limitation of this thesis is the limited number of interviews conducted that could have been higher and encompass more stakeholders and including their perspectives to further strengthen the analysis. Therefore, a broader industry-wide analysis is needed taking larger population, including other stakeholder networks.

For example, only one OEM accepted to participate in the interview, which may introduce bias and limit the diversity of perspectives from different OEMs. To mitigate this sort of bias throughout the study, findings were triangulated with data from available literature, consultation with experts to validate the findings, and websites and industrial reports (grey literature) to enhance reliability.

As a natural result of the learning process during the conduction of interviews, new questions emerged, and the importance of several other topics highlighted. Thus, as this thesis was limited by time being the most significant, further work can be performed to capture a more comprehensive view of individual aspects of the influences of DIs and on demand manufacturing business models on spare parts management and the sustainability aspect of it. Although there are many interesting topics can be studied in this area, I would recommend the following topics for further work to:

Incorporate leadership effects on DIs' governance in the Norwegian O&G industry

Develop a framework for efficient management of physical and digital inventories

- Investigate:

The convergence of OT (Operational Technology) and IT (Information Technology) via DI in the Norwegian O&G industry

API economy for DIs and data integrity over several DI platforms

Cybersecurity for DIs

The influence of DIs on Maintenance management

Risk management with regards to DIs' formations

How innovation and customization can be empowered by various DI formations, and

Waste management through DIs.

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A Appendices

A-1 Interview guide

Spare parts management

1. What are the current three biggest challenges of spare parts management you are experiencing, or you see in the Norwegian Oil and gas industry?
2. On a scale of 0 to 5, what would you rate the customization level for the spare parts the Norwegian oil and gas industry?
3. In your opinion, is the price for AM parts a barrier for the acceleration of using this technology more to respond to the market demand?
4. Based on NORSOK Z-008, there are three main categories of spare parts, Capital, operational, consumables. (Then the description of each category was given) in your opinion, which category of spare parts based on this standard, has more potential to be stored in DIs and produced on demand?

DIs and DIs' setting comparison

1. What do you think about the three key strategic benefits and three key challenges of participating in DIs for your company to provide services, and could further enhance the innovation of your solutions?

- Regarding the questions seeks participants preference for DI formation, as it is mentioned in section 5-1 with more detail, due to the novelty of the discussion about DI formations and clarify the concept, DI formations were described according to the visualization in section 4-7, Figure 7)

2. In your opinion, which DI setting offers a more transparent, secure, and efficient flow of information between parties?
3. In your view, which DI setting do you believe can facilitate the qualification process of additively manufactured spare parts more efficiently?
4. In your opinion, which form of centralized or decentralized setting can facilitate a trustworthy and robust cluster of 3D manufacturers to support the supply chain in the O&G industry? How?
5. Between Centralized and decentralized DI settings, which one do you think can lead to more sustainable outcomes (regarding spare parts management)?
6. In your perspective do you think repairment can become one of the main DI services? Follow up question: Do you think there is good awareness about these services in the industry?

7. Do you think an active participation in DI would open new markets and enhance your company's innovation?

On demand manufacturing

1. In your opinion, what are the three biggest challenges of localized manufacturing of spare parts?
2. Based on the current market conditions, do you see a lack of regulations for qualification for spare parts?
   Follow up questions: In your opinion, has AM reached to the maturity to be able to print safety critical spare parts?
   Does DNV active participation in DI platforms can lead to build up more trust in DI among the parties?
3. When it comes to licensing for spare parts, which scenario do you consider optimal for critical parts: fixed fee only, royalty fee only, or a mix of both?
4. Considering the three pillars of sustainability, how do you think utilization of DIs can contribute to those elements?
   Follow up question: On a scale of 0 to 5, how would you rate the lack of knowledge and competence regarding AM and DI in the Norwegian O&G industry?
5. In your opinion, could embracing new on-demand manufacturing business models result in decreased or increased transportation loading?

A-2 Python code sample

Here, a python code sample is included to demonstrate how the visualizations used in the thesis are made. This particular code used to visualize the data based on participants responses with regards to the current customization level of spare parts within the context of the Norwegian O&G industry. (Figure 15, section 5-2-4)

```
import pandas as pd

import matplotlib.pyplot as plt

# Adding responses data

data = {

    'Company no.': [

        'company no.1', 'company no.2', 'company no.3', 'company no.4',

        'company no.5', 'company no.6', 'company no.7', 'company no.8',

        'company no.9', 'company no.10', 'company no.11', 'company no.12',

        'company no.13', 'company no.14', 'company no.15'

    ],

    'Spare part category': [

        '2', 'Case dependent', 'Case dependent', 'Case dependent',

        '3', '1', '2', '2, Case dependent',

        '3', '3, Case dependent', '3, Case dependent', '3',

        '1', '2', '2'

    ]

}

df = pd.DataFrame(data)


# Cleaning the data

df_exploded = df.assign(Spare_part_category=df['Spare part category'].str.split(', 
')).explode('Spare_part_category')
```

```
# Filter out "Case dependent" when they appear with another category
df_exploded = df_exploded[~((df_exploded['Spare_part_category'] == 'Case dependent') &
                            (df_exploded.duplicated(subset=['Company no.'], keep=False)))]

# Counting the occurrences of each level for each spare part category
category_counts = df_exploded['Spare_part_category'].value_counts().sort_index()
# Defining colors for bar chart
colors = ['#add8e6', '#87CEEB', '#4682B4', '#1E90FF', '#4169E1', '#0000FF']

# Plotting the horizontal bar chart
plt.figure(figsize=(10, 6))
bars = plt.barh(category_counts.index, category_counts.values,
color=colors[:len(category_counts)])
plt.title('Customization Levels of Spare Parts', fontname='Times New Roman', fontsize=14)
plt.xlabel('Number of Companies', fontname='Times New Roman', fontsize=12)
plt.ylabel('Customization Level', fontname='Times New Roman', fontsize=12)
plt.xticks(fontname='Times New Roman', fontsize=12)
plt.yticks(fontname='Times New Roman', fontsize=12)

# Adding count labels next to each bar - tnx tDAriya
for bar in bars:
    width = bar.get_width()
    plt.text(
        width + 0.1, bar.get_y() + bar.get_height() / 2, f'{width}', ha='left', va='center',
        fontname='Times New Roman', fontsize=10, color='black'
    )
plt.show()
```