Sustainability challenges and how Industry 4.0 technologies can address them: A case study of a shipbuilding supply chain

Jo Wessel Strandhagen[a]*, Sven-Vegard Buer[b], Marco Semini[a], Erlend Alfnes[a] and Jan Ola Strandhagen[a]

[a]Department of Mechanical and Industrial Engineering, NTNU – Norwegian University of Science and Technology, Trondheim, Norway; [b]Department of Technology Management, SINTEF Digital, Trondheim, Norway.

**S.P. Andersens veg 3, Department of Mechanical and Industrial Engineering, NTNU, 7031 Trondheim, Norway, email: jo.w.strandhagen@ntnu.no*

Jo Wessel Strandhagen is a Ph.D. candidate at the Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology in Trondheim, Norway. In his Ph.D. studies, he is looking into the use of digital technologies in engineer-to-order manufacturing, with a particular focus on shipbuilding and shipyard logistics.

Sven-Vegard Buer is a research scientist at SINTEF Digital in Trondheim, Norway. He is currently working on a range of research projects in the areas of digitalisation in manufacturing and supply chains, lean manufacturing and mass customisation. In his Ph.D. studies, he investigated the relationship between lean manufacturing and Industry 4.0.

Marco Semini is an associate professor at the Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology in Trondheim, Norway. He holds a Ph.D. in Manufacturing Logistics. His research activities focus on manufacturing strategy and supply chain management, especially within shipbuilding.

Erlend Alfnes is an associate professor at the Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology in Trondheim, Norway. He holds a Ph.D. in Manufacturing Logistics. His research activities focus on manufacturing strategy, lean manufacturing and the integration of lean manufacturing and Industry 4.0.

Jan Ola Strandhagen is a professor in Manufacturing Logistics at the Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology in Trondheim, Norway. He holds a Ph.D. in Manufacturing Logistics. His research activities focus on production planning and control and sustainable manufacturing and logistics.

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The shipbuilding industry is under significant economic pressure and in need of more efficient solutions to secure economically sustainable operations. As a labour-intensive industry, it is also challenged by social issues and the need for a greener maritime industry is critical. Accordingly, the shipbuilding industry is pressured across all three dimensions of sustainability. This paper aims to identify the sustainability challenges that are present in shipbuilding supply chains and explore how the application of Industry 4.0 technologies can impact the sustainability of shipbuilding. This is achieved through a case study of a shipbuilding supply chain, which results in the identification of its primary sustainability challenges. The identified sustainability challenges related to social performance are working conditions and supplier relationships and communication, those related to environmental performance are emissions, energy-efficiency and end-of-life handling of ships, while those related to economic performance are productivity and cost-efficiency. Further, this work proposes a set of nine digital solutions to support sustainable operations in shipbuilding as the paper's primary contribution. This lays the foundation for further empirical research on sustainability and digitalisation in shipbuilding, while for practice the paper provides enhanced insight into how Industry 4.0 technologies can be adopted in their shipbuilding supply chains.

Keywords: engineer-to-order manufacturing; shipbuilding; digitalisation; Industry 4.0; sustainability

1 Introduction

The shipbuilding industry has been under significant economic pressure since 2008 (OECD 2018) and efficient and sustainable solutions for operations and supply chain management can contribute to getting out of the crisis. Shipbuilding companies across the world have for several years operated in a challenging market environment, with an order book that is currently as low as half the level of its peak in 2008 (OECD 2018). One important factor contributing to the challenging market environment is the drastic reduction in the price of oil, especially since 2015 (Menon Economics 2019). This dramatically impacted the demand for new ships when it shifted from ships for the oil and gas industry to ships for recreational purposes, such as cruise ships and ferries (OECD 2018). Accordingly, many shipyards are in a current phase of adjusting to the new market and are therefore under a significant amount of pressure to improve their economic sustainability so that they can remain in business. With this economic pressure in the shipbuilding industry, there has also been a consistently increasing focus on a greener and more socially responsible maritime industry (Para-González and Mascaraque-Ramírez 2020; Lee and Nam 2017). As such, attention to the environmental and social performance of shipbuilding is also required. While it is significant that the maritime industry contributes to achieve the United Nations' (UN) Sustainable Development Goals (SDGs), there is a lack of research on this matter (Wang et al. 2020).

Shipbuilding supply chains can be classified as engineer-to-order (ETO) supply chains, where the design, engineering, purchasing and production processes are performed after an actual order from a customer has been received (Mello et al. 2017). The ETO approach applies naturally to shipbuilding, as the ships are based on a shipowner's (i.e., the shipbuilding company's customer) specific requirements. Moreover, shipbuilding is of the most complex types of ETO manufacturing and involves the production of large, highly customised and complex products that require thousands of engineering hours (Willner et al. 2016). The characteristics of these types of products have major implications on the efforts of operations and supply chain management to achieve economic sustainability. The ETO approach makes this type of manufacturing more complex and dynamic than repetitive manufacturing approaches (Birkie and Trucco 2016), which complicate the production process. The peculiarities of the approach require tailored managerial paradigms, methods and supportive tools to be effectively and efficiently management (Adrodegari et al. 2015), as most approaches for improvement are intended for repetitive manufacturing (Seth, Seth, and Dhariwal 2017). Nevertheless, cost-effective solutions for ETO industries like the shipbuilding industry remain scarce. Thus, the shipbuilding industry is in need of new and more efficient solutions for operations and supply chain management so that it can both secure the economic performance of shipbuilding operations and satisfy the social and environmental dimensions of sustainability.

Industry 4.0 technologies carry a significant potential to improve industrial performance (Dalenogare et al. 2018). Building upon base technologies, such as the Internet of Things (IoT), cloud services, big data and analytics, Industry 4.0 contributes to smart supply chains, smart manufacturing, smart working and smart products (Frank, Dalenogare, and Ayala 2019). However, although the new and emerging technologies within Industry 4.0 tools can enhance sustainable operations (de Sousa Jabbour et al. 2018), further research is required to investigate how they can accomplish this (Machado, Winroth, and Ribeiro da Silva 2020).

The shipbuilding industry is lagging behind other industries in manufacturing when it comes to digitalisation (Zennaro et al. 2019; Sanchez-Gonzalez et al. 2019; Stanić et al. 2018). While some digital solutions have been proposed for specific areas of the shipbuilding supply chain, their connection to sustainability remains unclear (Ramirez-Peña et al. 2020). As a result, there exists a need to increase knowledge about how Industry 4.0 technologies can be leveraged to address the sustainability challenges that are currently present in shipbuilding.

To address these industrial challenges and the identified gap in research, this paper aims to identify the sustainability challenges that can be found in shipbuilding supply chains and explore how the application of Industry 4.0 technologies can address them. This is achieved through a case-based study of a shipbuilding supply chain and is complemented by a review of relevant literature within shipbuilding, ETO manufacturing, sustainability and Industry 4.0 technologies. While a recent case study investigates the application of Industry

4.0 technologies in the construction industry (Patrucco, Ciccullo, and Pero 2020), which is another type of ETO industry, studies in the shipbuilding industry remain limited. Thus, the current study sets out to contribute to the literature on supply chain management in ETO industries. Throughout the paper we include the three dimensions economic, environmental and social performance, i.e. the triple bottom line, in our understanding of sustainability (Carter and Rogers 2008). Moreover, the paper follows the natural-resource-based view (Hart 1995), wherein addressing environmental and social challenges is seen as a source of competitive advantage (Touboulic and Walker 2015).

The remainder of the paper is structured as follows: section 2 reviews existing literature on shipbuilding, sustainability and digitalisation; section 3 describes how the research is designed and summarises the research questions (RQs) and the case study approach that the study adopts; section 4 presents the findings from the case study; section 5 synthesises the case study findings and reported applications and solutions in published literature to outline possible solutions for enhancing sustainability through the use of Industry 4.0 technologies; section 6 discusses the paper's results and findings; and section 7 concludes the text by summarising its primary contributions and by addressing the study's limitations and opportunities for further research.

2 Literature review

2.1 Characteristics of the shipbuilding supply chain

From the perspective of operations and supply chain management, the characteristics of shipbuilding are similar to those of large, highly customised products as a whole (Zennaro et al. 2019). This type of ETO production is characterised by ambiguity in product specifications, which are highly dependent on customer requirements, and fluctuations and uncertainty in the mix and volume of sales over short and intermediate lengths of time

(Bertrand and Muntslag 1993). This results in further uncertainty and a complicated flow of material and information. Because ships are complex and highly customised products that are manufactured at a low volume, the product variety in finished products is high and they are often one-of-a-kind. As shipyards are organised with fixed positional layouts, which are typical of non-repetitive production systems (MacCarthy and Fernandes 2000), their internal logistics can be quite complex. This highly customised production also makes it difficult for them to achieve efficient and cost-effective automation (Joe and Chang 2017). Thus, when compared to other, more repetitive types of production, manual labour is still prominent in this type of manufacturing (Sjøbakk, Thomassen, and Alfnes 2014). The degree of automation in shipbuilding is considerably limited, as shipbuilding operations are rarely repeatable (Para-González and Mascaraque-Ramírez 2020). As of today, shipbuilding is a global business that involves several companies across many countries (Mello and Strandhagen 2011). Suppliers play a major role in shipbuilding projects, as up to 80% of the value that is invested into the completed products is produced externally (Held 2010).

Because the activities of design, engineering, procurement and production are driven by customer orders in ETO and shipbuilding supply chains (Mello et al. 2017), there are also peculiarities in the structures and contents of supply chain processes. Table 1 shows the main supply chain processes and their respective activities in a shipbuilding supply chain.

Table 1: Main supply chain processes in shipbuilding (adapted from Nam et al. (2018) and Mello et al. (2017)).

Processes	Activities
Sales	• Identify shipowner's requirements. • Develop concept design (propose feasible concepts based on shipowner's requirements). • Negotiate and determine price, delivery, contractual terms and penalties.
Design	• Design ship systems and arrangements. • Engineering (generate 3D models, define technical specifications, make detailed production drawings).

Purchasing and procurement	• Select suppliers, make quotations, and purchase materials and equipment. • Follow up and manage inbound materials.
Manufacturing	• Fabricate pipes, steel accessories and blocks to assemble the hull. • Assemble and install the equipment in the hull (outfitting) • Commissioning of the ship (perform inspections, trials and tests to ensure that the ship is ready to operate and that contractual requirements have been met)

The main actors in a shipbuilding supply chain include the 1) shipowner, 2) ship designer, 3) shipyard, 4) main equipment suppliers and 5) other suppliers (Mello et al. 2017). Since all actors are heavily involved throughout the entire process, the ability to coordinate operations across multiple companies is essential to avoiding delays (Mello, Strandhagen, and Alfnes 2015). For a more detailed overview of the actors' roles in the different supply chain processes, please see Mello et al.'s (2017) article.

2.2 Sustainability in shipbuilding and the shipbuilding supply chain phases

In the World Commission on Environment and Development's report, 'Our Common Future', sustainable development was defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland 1987). Since then, the term has received significant attention from researchers, supply chain managers and manufacturers (Ansari and Kant 2017). Carter and Rogers (2008) provided a more recent definition of sustainability, which has since been well established in supply chain management literature. Their definition was built on the triple bottom line concept and argued that the sustainability of an organisation consists of the three components of economic performance, environmental performance and social performance. Following this definition, a company's performance in the three dimensions can be measured by stand-alone performance metrics for each dimension (Yun et al. 2019).

In general, a company's social bottom line performance involves the impact of an operation on the quality of people's lives (Slack, Brandon-Jones, and Johnston 2013). Social issues in operations and supply chain management includes aspects such as philanthropy, safety, equity, health and welfare, ethics and human rights (Mani et al. 2016). Manufacturers in a supply chain also have a social responsibility to their suppliers and customers, as these entities have the ability to influence conditions for their fellow supply chain actors that result in specific social outcomes (Klassen and Vereecke 2012). Thus, the social dimension of sustainability related to the manufacturing of a product goes beyond a given firm's operations. Some examples of social performance measures include safety performance, work conditions, worker health, the buyer-supplier relationship and sustainable procurement (Yun et al. 2019). In shipbuilding, key measures of social performance are related to work conditions, as shipbuilding is a labour-intensive industry. Moreover, as shipbuilding is such a globalized industry, the relationship and communication with supply chain actors is another important sustainability measure (Para-González and Mascaraque-Ramírez 2020).

Operations and supply chain management can also significantly impact the economic bottom line, and economical sustainability is necessary for a company to stay in business (Slack, Brandon-Jones, and Johnston 2013). Economic performance includes specific and quantifiable measures, such as price, costs (savings), profits, sales growth and productivity/efficiency, in addition to more qualitative measures, like quality, customer satisfaction, reputation, competitive advantage and firm attractiveness (Yun et al. 2019). Especially relevant measures in shipbuilding are the production cost of each shipbuilding project, the time spent to deliver the project, and the quality associated with the delivered ship and the shipbuilding process (Pires Jr, Lamb, and Souza 2009).

Environmental performance, which also is the responsibility of operations management, is the third measure on the triple bottom line of an organisation's sustainability performance (Ansari and Kant 2017). The process of manufacturing products and extracting raw materials impacts the environment because these activities consume natural resources and produce emissions. The material consumption associated with the different shipbuilding processes is a key measure of sustainability in shipbuilding (Tuan and Wei 2019). In addition, there exist a number of environmental issues that are related to the movement of materials through a supply chain, including the transportation of materials and products during different stages of a supply chain and the handling of products during their end-of-life phase by scrapping, reusing, recycling or remanufacturing them (de Sousa Jabbour et al. 2018). For shipbuilding, the energy consumption in the different processes and the emissions and waste throughout the shipbuilding supply chain are the most relevant sustainability measures (Tuan and Wei 2019).

The maritime industry plays a vital role in global sustainability and is associated with each of the UN's SDGs (Wang et al. 2020). Table 2 presents relevant measures of sustainability performance in shipbuilding.

Table 2: Relevant measures of sustainability performance in shipbuilding.

Sustainability measures	Description	References
<u>Economic performance</u>		
Production cost	Labour costs, which depends on the volume of man-hours employed and labour unit costs.	Pires Jr, Lamb, and Souza (2009)
Time to delivery	Time between contract and delivery.	Pires Jr, Lamb, and Souza (2009)
Quality	The quality of the ship, the shipyard's flexibility and technical capability to take care of the owner's requirements, availability and efficiency of after-sales services and warranties and reduced need for supervision during construction.	Pires Jr, Lamb, and Souza (2009)
<u>Environmental performance</u>		
Material consumption	Material consumptions associated with steel fabrication, equipment manufacturing and outfitting processes.	Tuan and Wei (2019)
Energy consumption	Energy consumption in the suppliers' processes, transportation to the shipyard, shipyard processes and the ship operation phase.	Tuan and Wei (2019)

Emissions and waste	Emissions (to air and water) and waste from suppliers’ processes, transportation to the shipyard, shipyard processes and the ship operation phase.	Tuan and Wei (2019)
Social performance		
Working conditions	Workers’ workplace safety, health, stress and the repetitiveness of workers’ tasks.	Joe and Chang (2017)
Relationship and communication with supply chain actors	Transparency and visibility in communication and information sharing and relationship with main suppliers, partner shipyards and shipowners.	Para-González and Mascaraque-Ramírez (2020)

To improve sustainability and address the UN’s SDGs, the impact that companies have on sustainability should be evaluated. A holistic assessment of supply chain sustainability requires a look at the all supply chain phases products in the chain goes through (GRI, UN Global Compact, and WBSCD 2015). This type of assessment allows for the identification of factors that affect sustainability by considering the issues related to raw materials, the supply base, transportation and logistics, production, product use and the product’s end of life (i.e., the product's total lifecycle) (Jonsson 2008). For the purposes of this paper, we define the shipbuilding supply chain by five supply chain phases (see Figure 1). These phases are reviewed in the paragraphs below.

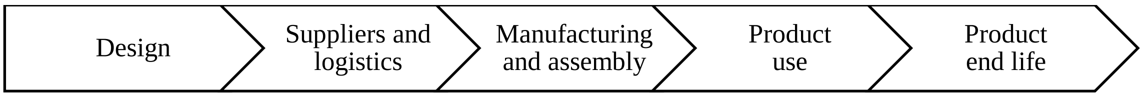

Figure 1: The shipbuilding supply chain.

2.2.1 Design

The ship design phase establishes an important foundation for the production process, the product use phase and the product’s end of life. Due to the distinct characteristic that each new customer order for a ship penetrates in the ship design phase, the design cost of and lead-time are connected to each unique shipbuilding project. As a result, there is a particular need in ETO companies to effectively share knowledge and information during the design phase and in the interfaces between design, procurement, production and project management. In order to ensure cost-efficient operations, it is also vital that these organisations maintain data records of design, components and subsystems (Hicks, McGovern, and Earl 2000).

Ideally, the product design should take into account the lifecycle cost and environmental impact of the design (Ameli, Mansour, and Ahmadi-Javid 2017). This is because a majority of the sustainability-related decisions are taken in the design phase, which thereby indirectly affects the sustainability in later supply chain phases. As an example, the overall energy-efficiency of ships in operation depends on the design process and particularly the design of the hull form (Ang et al. 2017). Thus, optimising the design of the hull form can improve energy-efficiency, which influences both environmental and economic sustainability.

2.2.2 Suppliers and logistics

Shipbuilding has become a global business, and sourcing can cover almost any phase performed in the shipyard (Mello and Strandhagen 2011). As an example, most larger ships delivered from Norwegian yards have a significant part of their steel structure produced at locations in Eastern European countries, such as Poland, Ukraine, Romania, and Turkey (Semini et al. 2018). Inter-firm coordination between the many suppliers and actors in a supply chain is critical to improving performance in shipbuilding (Mello and Strandhagen 2011).

Furthermore, sustainable supply chain management requires cooperation among partnering companies (Seuring and Müller 2008), which is challenging due to the barriers to collaboration in ETO supply chains (Stavrulaki and Davis 2010). Gosling et al. (2015) describes the need for more holistic control of ETO supply chains, with information transparency that makes inventories, specifications, work-in-progress, flow rates, and orders visible throughout the supply chain. The differences in the information systems that various companies use is one example of a barrier to such control that impacts shipbuilding supply chains (Mello and Strandhagen 2011).

2.2.3 Manufacturing and assembly

Efficiency in the planning and coordination of production activities is difficult in the ETO approach due to the highly complex, dynamic and uncertain flow of materials and information (Bertrand and Muntslag 1993). Achieving and maintaining sustainable performance in an ETO industry requires cost-efficient operations (Birkie, Trucco, and Kaulio 2017). This is particularly challenging within the ETO context, as most approaches for increasing cost-efficiency are developed for mass production systems (Seth, Seth, and Dhariwal 2017). In addition, the complexity, uncertainty and dynamism of the ETO manufacturing environment generate a need for integrated information technology (IT) solutions that can track the progress of different manufacturing phases, share drawings in different formats, manipulate technical requirements, validate simulation models, etc. Mello and Strandhagen (2011) argue that the shipbuilding industry is struggling to keep up with other industries in applying new technologies to achieve these goals.

There are also issues related to social sustainability in this type of manufacturing, especially when it comes to working conditions. Although automation is continuously increasing in the shipbuilding industry, working conditions are still characterised by large amounts of manual labour that require workers to make awkward and unsafe motions (Joe and Chang 2017).

2.2.4 Product use

Ship operation, which also result in marine pollution and emissions, is the most energy-consuming phase of a ship's lifecycle (Ang et al. 2017). Thus, researchers must pay close attention to this phase when assessing the sustainability of the shipbuilding industry. The main aspects of the ship operation phase are the ships' fuel type and energy-efficiency. Both are dependent on the design phase, where there is the potential to design ships that run on clean fuel and have optimised hull shapes and specifications that fit within an intended type of operation (Rahman and Karim 2015).

Another aspect of the use and operation of ships is related to the industries they support, one of which includes the oil and gas industry. Although the oil and gas industry contributes to job generation, energy access, government revenue, etc., it can negatively impact sustainability due to its environmental footprint on biodiversity, its contributions to climate change and its associated impacts on communities (UNDP, IFC, and IPIECA 2017).

2.2.5 Product end life

The number of ships that go out of service is increasing significantly every year, and the current status of the sustainability of the ship recycling industry is unsatisfactory (Alcaide, Rodríguez-Díaz, and Piniella 2017). The end of life phase is critical to achieving sustainability and moving towards a circular economy. Remanufacturing contributes to all three dimensions of sustainability because it saves materials and energy, prevents waste, creates jobs and provides more savings than the production of new goods with new components (Jansson 2016). However, due to the characteristics of ships and their supply chains, remanufacturing in shipbuilding is met by several challenges related to the infrastructure and reverse supply chains that are required to make the process financially feasible (Jansson 2016; Ali et al. 2015). In addition, product characteristics, such as complex and customised components and products, make it difficult to incorporate strategies and practices for remanufacturing, recycling or reusing ships (Jansson 2016). Milios et al. (2019) argue that the reuse and remanufacturing rates for ship equipment are low when compared to the aviation and automotive industry by identifying the barriers to reuse and remanufacturing, such as high costs and a lack of organisational competence.

2.3 Industry 4.0 technologies in manufacturing and supply chains

Digitalisation and the technologies within Industry 4.0 are expected to cause disruptive changes to industrial production (OECD 2017). These changes involve organisational structures, business processes, business models and the creation of smart manufacturing environments (Kagermann, Helbig, and Wahlster 2013; Lasi et al. 2014; OECD 2017). When broken down, Industry 4.0 is comprised of a number of technological advancements (Wang et al. 2016). These include innovations to existing technologies and the development of entirely new technologies. Through automatic identification technology such as radio frequency identification (RFID), sensors and the IoT, identification and interconnectivity allow for real-time data collection during every step of a supply chain (Wang 2014). Decision supportive technologies and concepts, which include artificial intelligence, big data analytics and machine learning, enable efficient and effective decision making. In addition, seamless information flow technologies and concepts, such as integrated IT systems, real-time control and cloud services, can improve coordination by allowing companies to share information between all actors within a supply chain. New technology such as 3D printing, autonomous mobile robots (AMRs) and collaborative robots, can contribute to the production of highly autonomous factories that reduce costs and increase productivity (Frandsen et al. 2020; Fragapane et al. 2020; Djuric, Urbanic, and Rickli 2016). Frank, Dalenogare, and Ayala (2019) proposed a framework that divides Industry 4.0 technologies into the base technologies and front-end technologies. The base technologies include the IoT, cloud services, big data and analytics, while the front-end technologies consists of the four dimensions smart manufacturing, smart products, smart supply chains and smart working. Base technologies support and are present in every dimension of front-end technologies that enable Industry 4.0 (Frank, Dalenogare, and Ayala 2019).

The benefits to companies that adopt Industry 4.0 technologies are numerous and can include improved product quality, reduced operational costs, increased productivity, improved sustainability and improved worker satisfaction (Dalenogare et al. 2018). More specifically, automating business processes through the adoption of Industry 4.0 technologies can contribute to reductions in energy demand, emissions and required manhours (Munsamy, Telukdarie, and Fresner 2019). Thus, Industry 4.0 carries the potential to fundamentally improve organisational sustainability (Waibel et al. 2017). Stock and Seliger (2016) presented an overview of the opportunities for sustainable manufacturing that would follow Industry 4.0 developments and the digitalisation of manufacturing. They provided both the macro and micro perspectives of Industry 4.0 with general considerations and connections between sustainability, digitalisation and manufacturing. de Sousa Jabbour et al. (2018) more explicitly explained how specific Industry 4.0 technologies can improve sustainability at a conceptual level.

When it comes to discussions about the shipbuilding industry, sustainability and Industry 4.0 are mainly described and connected through general and conceptual terms. For instance, Stanić et al. (2018) outlined the future of the shipbuilding industry by incorporating recent and emerging technological developments and proposing a methodology for the implementation of Industry 4.0. Moreover, Ramirez-Peña et al. (2020) conducted a conceptual analysis on how Industry 4.0 is applicable to different supply chain paradigms and provided suggestions for the shipbuilding industry. In spite of these existing research studies, the number of empirical investigations on Industry 4.0 and sustainable operations in the shipbuilding industry remains limited.

3 Research methodology

By considering the industrial challenges and existing literature that have been assessed in previous sections of this paper, it is possible to frame a research topic, develop suitable RQs and establish a research methodology for the study. Figure 2 shows this paper's research methodology, and each main step is described in the four subsections that follow.

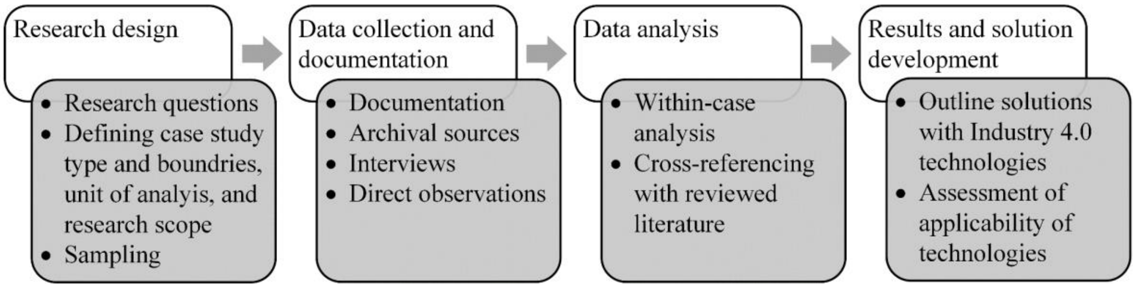

Figure 2: The current study's research methodology.

3.1 Research design

To ensure the validity and reliability of the present case study, this research was designed according to the principles presented by Yin (2009). The first step of the research methodology defines suitable RQs, selects a research method and determines the selected case company. To reach the aim of the paper, we formulated the following RQs:

- RQ1: What are the main sustainability challenges in the different shipbuilding supply chain phases?
- RQ2: How can Industry 4.0 technologies address the sustainability challenges identified in each shipbuilding supply chain phase?

The aim of RQ1 is to identify how shipbuilding, with its characteristic products, processes and supply chains, creates sustainability-related challenges. Further, the question facilitates the identification of the different phases of the shipbuilding supply chain where these challenges are present. Building on the results of this, RQ2 aims to explore the impact on the three dimensions of sustainability from the application of Industry 4.0 technologies in a shipbuilding supply chain. This question is linked to the different phases of the shipbuilding supply chain in the same manner as RQ1.

To address the RQs of the study, a single case study was chosen as the case study design type. While the single case study design type allows for greater depth, it also limits the generalizability of the conclusions that can be drawn (Voss, Tsikriktsis, and Frohlich 2002). We chose a single case study design because the selected shipbuilding supply chain was representative, typical and applicable to the study's RQs. When the objective is to capture the circumstances or conditions of a common situation, a single case is suitable (Yin 2009).

The single case that was selected for this study was a shipbuilding company and its supply chain that have collaborated on research activities with the authors of the present work for over a decade. The authors' strong relationship with the case company allowed access to the data sources that are described in the following subsection. Additional details on the shipbuilding company and its supply chain are presented in section 4.

3.2 Data collection and documentation

Data were collected from four primary sources: documentation, archival records, interviews and direct observations. The documentation and archival records included results from a four-year research project that spanned from 2013–2017 and in which three of the authors were heavily involved. Since then, the study has involved three site visits at the selected shipyard by four of the authors. The involvement of several researchers in the study, the use of multiple evidence sources and the use of several informants in the case company are the main measures that were taken to protect against bias. Table 3 describes how the current study used its data sources. Each source had its respective strengths and weaknesses (Yin 2009), and accordingly, the data collection process was designed to include multiple sources of evidence to reduce the impact of each source's weaknesses and address potential problems in construct validity through data triangulation. Data were documented in parallel with the data collection process, and the authors made detailed write-ups of the sites they visited as soon as possible after each visit.

Table 3: Sources of evidence used in the study.

Source of evidence	Use in this study
Documentation	Minutes of research project meetings and project reports. Previously carried out research projects involving the shipbuilding company included different types of documentation describing the shipbuilding company, and issues relevant in the context of this study. Such documents were included in the case data collection process.
Archival records	Various company records, such as list of ship deliveries, annual reports, homepages, and news articles. Such records are typically open access, and were used to enhance the researchers understanding of the shipbuilding industry and the case company and its supply chain.
Interviews	The interviews took the form of semi-structured, 'focused interviews' (Yin 2009, p. 109) and were held with three representatives of the shipbuilding company (the Deputy Managing Director and two business analysts). Each interview had a duration of between 1 and 2 hours. The interviews were focused on the shipbuilding company's supply chain and operation, and aimed at increasing the researchers understanding of eventual sustainability challenges present in the shipbuilding supply chain. The interviews took place at three different occasions between December 2018 and December 2019.
Direct observations	Three site visits at the shipyard and one site visit at a main equipment supplier of the shipyard. The site visits included yard tours guided by one or two representatives from the shipbuilding company, and were focused on the yard operations, including material and information flow internally at the yard and between the shipyard and other supply chain actors.

3.3 Data analysis

Data were analysed through the construction of an array and display of the data by following the structure of the shipbuilding supply chain. This enabled a systematic identification of the sustainability challenges that presented during the respective supply chain phases. These challenges were then cross-referenced with literature about shipbuilding, ETO manufacturing, sustainability and digitalisation. The literature search was aimed at identifying published articles and conference papers that addressed digitalisation or sustainability in the supply chains producing complex ETO products. The academic databases Scopus and Web of Science were used to search for the keywords listed in Table 4.

Table 4: Keywords used in the literature search.

"Sustainability" OR "digitalisation"		"Shipbuilding"
SUSTAINABLE SUSTAINABILITY GREEN DIGITALI*ATION DIGITAL TECHNOLOGIES INDUSTR* 4.0	*AND*	SHIPYARD SHIPBUILDING SHIP PRODUCTION ENGINEER-TO-ORDER ONE-OF-A-KIND

The initial search was limited to publications from 2009 until the present and resulted in 67 publications that included both conference papers and journal articles. After reviewing article abstracts and performing the snowballing procedure to find additional articles, a total of 21 articles were identified, reviewed and included specifically for the data analysis and subsequent solution development. Conference papers were included because they, due to undergoing a more rapid publication process than journal articles, may include novel digital solutions that are not yet published in journal articles.

3.4 Results and solution development

Following the shipbuilding supply chain structure, the case data and reviewed literature were synthesised to develop a range of solutions that incorporate Industry 4.0 technologies. Moreover, the applicability of the different technologies during each supply chain phase was established by investigating the various solutions. Each solution aims to address the identified sustainability challenges. The solution development process involved several iterations, revisions and attempts to collect additional support and input from existing literature, and it was subject to several workshops between the current paper's researchers and the case company's representatives.

4 Case findings: Sustainability challenges in the shipbuilding supply chain

The primary actor in the shipbuilding supply chain in the study is a shipbuilding company that covers the roles of both designing and constructing highly customized vessels. The company has traditionally built advanced offshore vessels, such as platform supply vessels, anchor-handling vessels, offshore construction vessels, and seismic vessels. In recent years, due to the decline in demand for offshore vessels, they have also included expedition cruise ships, yachts and passenger ships in their product portfolio, in addition to ships for the offshore wind industry. In its own shipyard, the company outfits entire ship hulls, which are constructed at a foreign shipyard that the case company is strategically partnered with. Other actors in their supply chain include their main equipment suppliers, the shipowner and other suppliers. This section presents the findings from the study of the case company's shipbuilding supply chain, covering all the phases of a shipbuilding supply chain from an operations management perspective and culminates in the identification of a set of sustainability challenges that are present across the various shipbuilding supply chain phases and their related case study evidence (see Table 5).

4.1 Design

The case company currently uses advanced technologies in its design department, where highly innovative designs are developed. A range of computer-based tools such as computer-aided design (CAD) are used to design ships that are cost-effective in operation and that consider capital expenditures, operational expenditures and the technical aspects of ships. However, because operational cost-efficiency is the primary target of the design phase, less attention is given to the environmental performance of the ships' operations. The design phase lays the groundwork for the ship operation phase, and decisions taken at the design stage affect the entire shipbuilding supply chain. The case company does not currently give significant consideration to the impact of ship design on the environmental performance of the ship operation phase.

The shipbuilding company's design phase is critical, time consuming and has a significant impact on the other shipbuilding supply chain phases. The shipyard is under constant pressure to initiate new activity at the yard, which rushes the process to finalise the design phase. This frequently results in poor quality design documents that affect engineering work and eventually production. The design phase is also obstructed by the inefficient flow of information between the company's design, procurement, production and project management departments, and information is often improperly shared with the relevant disciplines. This is further complicated by the need to consistently maintain an updated product database, as product changes are commonly necessary due to changing customer requirements or internal factors, such as the manufacturability of a designed solution. In other words, because the flow of information in the design process is inefficient and fragmented, it is challenging for the company to make timely updates to its product data.

4.2 Suppliers and logistics

Statements from interviews and discussions with the shipbuilding company indicate that the challenges associated with its global supply chain operations, such as managing the geographical distance between their own shipyard (i.e., the outfitting yard in the supply chain) and the shipyard that produces the ship hull, are prevalent. Communication and coordination are vital to ensuring that a hull is built according to customer requirements and delivered to the outfitting yard on-time. Additional efforts in the strategic development of the hull yard so that it meets quality and speed requirements are also necessary.

Assessing case data also show that the number of different information systems used is high, even within single companies in the shipbuilding supply chain, and information system integration is challenging. There is currently a lack of holistic control and information transparency between actors and within companies in the shipbuilding supply chain. This makes efficient coordination difficult and eventually impedes the economic sustainability of operations.

4.3 Manufacturing and assembly

The high share of non-value added activity that is performed by shipyard operators is a critical issue for the shipyard involved in this study, as there is a high potential to decrease business expenditures when efficiency and productivity are improved. A high share of non-value added activity can be due to the existence of widespread operations that make it difficult for the company to maintain an overview of its yard from a manufacturing and logistics perspective. Materials, tools and equipment are geographically dispersed and operators spend a considerable amount of their time searching for them, decreasing the shipyard's efficiency and productivity. Moreover, operators' tasks are highly dependent on work instructions and product drawings, which is currently predominantly paper-based. Thus, there is limited access to up-to-date information about tasks, and a proper integration between higher-level IT systems and the shop floor where operators perform their tasks is lacking.

Direct observations of the shipyard confirmed a low level of automation in the yard's operations and a large amount of manual labour. When compared to operators in modernised manufacturing companies, shipyard operators work in much harsher conditions, and several of their tasks are characterised by unsafe and awkward motions, such as lifting, carrying, stretching, etc., to handle the materials they need to perform their jobs. There is an evident lack of tools to support shipyard workers, and the level of automation and digitalisation at the yard site is low.

4.5 Product use

During the product use phase the shipyard has responsibilities related to after-sales and maintenance services that include the eventual repair of ship. These activities are important, especially since they enable the manufacturer to maintain a good relationship with their customers. However, there is also the potential to improve the factors that are related to cost-efficiency and quality during the after-sales, maintenance and ship repair processes. Although the ability to deliver spare parts to ships that have been built at the company’s shipyard is key to maintaining customer satisfaction, producing and delivering those parts adds further complexity to the supply chain. The process requires that the shipyard keep stock of spare parts, and the production of those spare parts can disturb the normal production of regular components.

Maintenance of the delivered ship’s different sub-systems is also vital to the product use phase, as high-quality maintenance can reduce the ship’s operational downtime. Maintenance prolongs a ship’s lifetime and requires good and accurate surveillance of the status of its various sub-systems. Currently, the shipbuilding company does not monitor ships in operation and the status of its sub-systems.

4.6 Product end life

When ships that have been built by the shipbuilding company enter the final stages of their lifecycle, the company can perform several potentially relevant activities. The shipyard is primarily involved in retrofitting ships with new equipment or interior and converting ships to make them suited for other kinds of operations. As an example, an offshore ship was recently retrofitted through the installation of a new battery power system from a diesel-electric vessel to a hybrid-electric vessel. These types of activities resemble the outfitting operations that are performed on new ships. They also encounter challenges that are similar to what has been listed above, including the need for paper-based documentation for operators to perform tasks and a high degree of manual labour.

However, the shipbuilding company is uninvolved in the end-of-life activities for ships where retrofitting or conversion are not relevant alternatives. Although the case company has discussed ship recycling as a possible future scenario, there is still a long way to go before this type of idea can be fully integrated into its supply chain, as ship recycling has yet to be sufficiently facilitated into its operations and the cost-benefit ratio for recycling is not currently at a satisfactory level.

Table 5: Overview of the identified sustainability challenges and the related case study evidence.

Shipbuilding supply chain phases	Sustainability challenges	Case study evidence
Design	Impact on ship's environmental performance during ship operation.	Ship design prioritizes operational cost-efficiency over improving environmental performance.
	Inefficient and fragmented flow of information.	Poor integration between design systems and those of other disciplines.
Suppliers and logistics	Global sourcing (low proximity between actors).	Ship hulls are produced at a foreign shipyard.
	Complex and inefficient flow of information between actors.	Several different IT systems used internally and between actors.
Manufacturing and assembly	Working conditions.	High amount of manual labour, awkward and unsafe motions required by shipyard operators and a lack of supporting tools.
	Productivity and cost-efficiency.	Vast yard site with a poor of overview of materials, time spent searching for and retrieving materials and information.
Product use	Emissions and energy-efficiency.	Shipbuilding company does not monitor ships in operation and the status of its sub-systems.
	After-sales services, maintenance and repair.	Spare parts production and stock-keeping disrupts normal production.
Product end life	Ship recycling.	Unsatisfactory end-of-life handling of ships produced in the supply chain.

5 Industry 4.0 technologies for enhanced sustainability in shipbuilding

As the case findings in section 4 indicate, there can be a number of challenges related to sustainability in shipbuilding supply chains. Moreover, these challenges span across all three dimensions of sustainability and all the shipbuilding supply chain phases. Although digitalisation through the application of Industry 4.0 technologies has been suggested for the shipbuilding industry to improve its competitiveness and sustainability (Ramirez-Peña et al. 2020; Stanić et al. 2018), specific applications of these technologies are still required. This section specifies nine potential solutions with the application of Industry 4.0 technologies to address sustainability issues in shipbuilding supply chains. These solutions are presented in Table 6 and explained in further detail in subsections that follow.

Table 6: How Industry 4.0 technologies can enhance sustainability in shipbuilding supply chains.

Sustainability challenges	Solutions for enhanced sustainability through Industry 4.0 technologies	References
Design		
Impact on ships environmental performance during ship operation.	Optimisation of ship design for increased energy-efficiency through advanced (CAD) solutions and advanced simulations (5.1).	Ang et al. (2017)
Inefficient and fragmented flow of information.	Effective sharing of knowledge and information between design, procurement, production and project management through advanced and integrated information sharing solutions (5.2).	Jagusch, Sender, and Flügge (2019); Stanić et al. (2018)
Suppliers and logistics		
Global sourcing (low proximity between actors).	Closer collaboration with suppliers through advanced information sharing solutions (5.3).	Stanić et al. (2018); Dallasega, Rauch, and Linder (2018)
Complex and inefficient flow of information between actors.	Increased information visibility and data availability through the application of RFID (5.4).	Pero and Rossi (2014)
Manufacturing and assembly		
Working conditions.	Improved working conditions and workplace safety through operator support such as wearables with sensors and augmented reality (AR) technology (5.5).	Blanco-Novoa et al. (2018); Joe and Chang (2017)
Productivity and cost-efficiency.	Increased productivity and efficiency of manufacturing logistics processes by IoT technology and integration of IT systems for managing material and information flow at the shipyard (5.6).	Jagusch, Sender, and Flügge (2019); Fernández-Caramés et al. (2018)
Product use		
Emissions and energy-efficiency.	Utilizing big data and installing sensors in products that feed information to the manufacturer so they can analyse and optimise it for future designs (5.7).	de Sousa Jabbour et al. (2018); Rymaszewska, Helo, and Gunasekaran (2017)
After-sales services, maintenance and repairs.	Additive manufacturing for the production of spare parts (5.8).	Jha (2016)
Product end life		
Ship recycling.	Establishment of a sustainable ship recycling industry, facilitated by cloud services and IoT, fostering job creation and reduced material and energy consumption (5.9).	DNV GL (2020)

5.1 Optimisation of ship design for increased energy-efficiency

During the design phase of shipbuilding, digitalisation primarily and directly affects economic sustainability by providing advanced simulations, CAD solutions and more efficient knowledge and information sharing that can increase the efficiency of design activities. An additional solution that can impact sustainability is the use of automated simulations during ship design to improve ship resistance and power consumption in the ship operation phase (Ang et al. 2017). Improving optimisation of the simulations during the design phase so that a ship is designed to be more energy-efficient can also indirectly influence a ship's environmental impact. With such a foundation laid during the design phase, sustainability improvements can be realised later during the ship operation phase.

5.2 Efficient sharing of knowledge and information

Industry 4.0 technologies can facilitate knowledge and information sharing much more efficiently than conventional technologies. Especially relevant technologies include those that enable real-time acquisition and data transfers. Auto-ID technologies, such as RFID and real-time location systems (RTLS), are well-suited to these purposes in the shipbuilding industry (Jagusch, Sender, and Flügge 2019). Adopting technologies that enable efficient sharing of information in real-time can drive the shipbuilding industry towards the digital era of the future (Stanić et al. 2018). To improve knowledge and information sharing between design, procurement, production and project management, a holistic digital data exchange must be established between the design and other supply chain stages (Jagusch, Sender, and Flügge 2019). Industry 4.0 technologies can facilitate this exchange.

5.3 Closer collaboration with suppliers

Industry 4.0 technologies for communication are changing the ways in which actors in a supply chain communicate and collaborate as they facilitate supply chain integration. Such an enhancement of supplier relationships could positively affect all dimensions of sustainability. Manufacturers have social responsibilities towards its suppliers (Klassen and Vereecke 2012), and such responsibilities can be taken easier with enhanced supplier relationships.

Industry 4.0 technologies could also impact the environmental dimension of sustainability by providing companies with the capacity to circumvent the need for geographical proximity and external coordinators to create industrial symbiosis (i.e., the association between industrial actors where the waste or by-products of one actor becomes the raw materials for another) and close material loops (Prosman, Wæhrens, and Liotta 2017). Dallasega, Rauch, and Linder (2018) investigated how Industry 4.0 technologies can enable proximity in construction supply chains where the physical and cognitive distance between actors in a supply chain is high, identifying several proximity enablers in the form of Industry 4.0 technologies. Proximity is also relevant to shipbuilding supply chains (Mello and Strandhagen 2011), which can benefit from Industry 4.0 technologies in a similar manner. Hence, Industry 4.0 technologies can facilitate closer collaboration between a shipbuilding company's suppliers, reducing the time and effort they would normally spend on coordinating the supply chain.

5.4 Increased information visibility and data availability

Pero and Rossi (2014) finds in their case study of a company producing vessels and heat exchangers in an ETO supply chain that an RFID-based data gathering and sharing system can both increase revenues and reduce costs for the company. Although not explicitly documented, the paper also argued for the corresponding benefits that this technology could bring to the supply chain as a whole. Nevertheless, Yu et al. (2016) surmised that ETO environments require tailor-made RFID system solutions because they are highly complex. Information visibility and rapid data availability are required for agile and competitive ETO supply chains (Stavrulaki and Davis 2010), and RFID and other data capturing and sharing technologies can efficiently achieve these aims. Thus, the use of RFID in logistics, both between suppliers/customers and shipyards, is a promising solution for enhancing economic and social sustainability that can facilitate integration, coordination and information transparency amongst supply chains.

5.5 Improved work conditions and productivity

The primary technological developments that support ship production include industrial robots and technologies that support operators, such as AR and virtual reality (VR). AR, VR and other types of visual technology (Mittal et al. 2017) can provide support to operators by displaying job schedules, product models, work instructions, etc. on tablets or wearables, such as smart glasses and helmets (Blanco-Novoa et al. 2018). In essence, making this kind of information available through wearables will improve the productivity of shipyard operators. Technology-empowered wearables can also improve working conditions and ensure better workplace safety for shipyard workers through real-time sensor-based warnings about potential risks in a worker’s surroundings during jobs on the yard (Joe and Chang 2017). In addition to placing more advanced robots on the worksite to take over the most physically demanding activities, this will improve the working conditions at shipyards. In summary, Industry 4.0 technology can enhance the social sustainability of shipbuilding and enable workers to concentrate on more complex and higher-level activities (Jagusch, Sender, and Flügge 2019)

5.6 Efficient manufacturing logistics

With the highly manual handling of materials and complex and often disrupted movement of materials within shipyards, automated and autonomous solutions for material handling can efficiently improve both economic and social sustainability. By using these solutions, products, components, tools and equipment can be more effectively transported across the yard and with less human intervention. In this way, Industry 4.0 technologies bring automation and autonomy to the physical movement of materials. However, although Industry 4.0 technologies, such as autonomous vehicles, are promising from a conceptual point of view, they are more representative of a potential future than the current state of reality (Morais, Danese, and Waldie 2016). Nevertheless, Sanchez-Gonzalez et al. (2019) identify several studies that developed systems, algorithms, and methodologies for the use of industrial robots in shipyards. Such an automation of production and logistics processes will enable more efficient manufacturing logistics.

Developments on the digitalisation of information flow in shipbuilding have come several steps further than developments in movement of materials, with pilot implementations of these technologies having already been documented (Fernández-Caramés et al. 2018; Jagusch, Sender, and Flügge 2019). Systems that realize real-time data transfers on the shop-floor promise to save time through the precise and clear communication of information to shop-floor workers, reducing the time they might otherwise spend in clarifying their duties or searching for missing information (Jagusch, Sender, and Flügge 2019). Combining the digitalised flow of information with item-tagging, sensors and AR-technology can further enhance a shipyard's productivity by helping operators locate items much more quickly than they do today (Fernández-Caramés et al. 2018). In summary, using Industry 4.0 technology to manage and streamline the complex flow of information in shipyards is key to achieving more sustainable manufacturing.

5.7 Continuous design optimisation

By installing sensors in products and networking products and components to create an industrial IoT, organisations can extend their value chains to better serve their customers (Rymaszewska, Helo, and Gunasekaran 2017). Embedding products with sensors can also benefit the circular economy, as these developments can enable better utilisation of equipment through performance monitoring of the products that are currently in operation (de Sousa Jabbour et al. 2018). With increased use of sensors and data collection tools in ship operations, considerable amounts of data can be analysed and feedback loops between operations and manufacturing can be established. In turn, this can pave the way for increased efficiency in ship operations. Similarly, technologies for weather routing and hull condition monitoring can also improve a ship's fuel consumption (Ang et al. 2017).

5.8 On-demand spare parts production

Additive manufacturing is a promising technology for the production of spare parts in manufacturing industry in general (Frandsen et al. 2020) and in the shipbuilding industry (Jha 2016). Because it can decrease the complexity of a supply chain by providing simpler and more effective solutions, reducing inventory and enabling a higher degree of material utilisation (Holmström and Partanen 2014), it has a clear impact on both economic and environmental sustainability. Nevertheless, there remains a need for further technological developments and quality issues to be addressed (Chen et al. 2015) before additively manufactured spare parts can become relevant, as these technologies are less capital intensive, more autonomous and offer shorter production cycles than the systems that are used today (Khajavi, Partanen, and Holmström 2014). When these developments are in place, additive manufacturing can be used to produce highly customised steel or smaller and more complex parts and facilitate substantial cost and time reductions in after-sales services in the shipbuilding industry (Jha 2016).

5.9 Improved end of life handling of ships

Finally, digitalisation can help shipbuilding companies to overcome some of the current challenges related to the reuse, remanufacturing and recycling of ships. The potential to provide a complete, digital overview of a ship and its components, in addition to the ability to make connections between existing ships that are currently in operation, can aid companies in surmounting the obstacles related to remanufacturing. This can be realised through the development of IT solutions, such as the web-based application IHM Green Server (IGS) by DNV GL (DNV GL 2020), a solution that gathers and processes ship component data and facilitates the ship recycling process (World Maritime News 2013). Moreover, survey-based research indicates that these technologies can improve sub-standard recycling yards by implementing monitoring systems of activity in the yards (Alcaide, Rodríguez-Díaz, and Piniella 2017). From there, Industry 4.0 technologies, such as cloud services and IoT, can be leveraged to build the necessary infrastructure to establish an economically sustainable business that is capable of handling the end-of-life phases of ships. In turn, this can affect social sustainability through the creation of jobs and a safer ship recycling industry, in addition to environmental sustainability through the reduction of material and energy consumption since fewer ships will be scrapped.

6 Discussion and managerial implications

The most developed digital solutions for the shipbuilding industry are those that address challenges in the *Suppliers and Logistics* and *Manufacturing and Assembly* phases. Of the identified solutions, the use of RFID to track and trace material (Pero and Rossi 2014) and the development of operator support through AR and VR (Blanco-Novoa et al. 2018) are those that are closest to becoming common practice. On the other hand, several of the solutions remain in a pilot phase (Fernández-Caramés et al. 2018; Blanco-Novoa et al. 2018) or at a conceptual or system development level (Dallasega, Rauch, and Linder 2018; Joe and Chang 2017; Ang et al. 2017; Jha 2016). Only a few early-stage industrial implementations have been identified (Jagusch, Sender, and Flügge 2019; Pero and Rossi 2014). In this regard, existing frameworks, such as the one proposed by Frank, Dalenogare, and Ayala (2019), may prove useful in guiding the industrial implementation of these possible digital solutions in the shipbuilding industry. Accordingly, shipbuilding supply chains should initially pay attention to the Industry 4.0 base technologies and investigate how they can be applied and pursue the least complex implementation level. This level includes cloud services, improved connectivity, monitoring and control of products, vertical integration of internal IT systems and the establishment of internal digital platforms (Frank, Dalenogare, and Ayala 2019). From there, the digital infrastructure that is needed can be built from the bottom, enabling for the pursuit of the more complex digital solutions that have been suggested in earlier sections.

Although the current implementation of Industry 4.0 technologies in ETO industries may be low, the wide range of conceptually described digital solutions that have been identified promise considerable benefits for the operations of ETO supply chains as a whole. In particular, the relevant technologies include those that can facilitate the principles for the design and operation of engineer-to-order supply chains that were established by Gosling et al. (2015). ‘Information transparency’ is one of these principles, and several of the solutions in section 5 address the need for expanded access to accurate and timely information in ETO supply chains, enabling improved coordination, efficiency and sustainability. This suggests the possibility for interesting opportunities and a promising potential for further improvements to the shipbuilding industry and ETO industries with similar characteristics. Nevertheless, it is evident that Industry 4.0 technologies are not universally applicable regardless of the industrial context. The peculiarities of the ETO context seem to affect the applicability of Industry 4.0 technologies, along the same lines as it affects the applicability of other paradigms within operations and supply chain management (Adrodegari et al. 2015). Therefore, because the unique nature of each ship and the low level of repetition in shipbuilding processes seem to impede the adoption of Industry 4.0 technologies, industry-specific approaches are necessary for Industry 4.0 technologies to be implemented into shipbuilding.

There are several barriers to the implementation of Industry 4.0 technologies (Raj et al. 2019) that may explain their relatively low levels of implementation within the shipbuilding industry. In particular, the lack of clarity regarding the economic benefit seems to be one of the main barriers to implementation, based on discussions with the case company representatives. They state that the recent decline in the shipbuilding market and its current economic state makes shipbuilders hesitant to implement any new technologies that do not present a clear, significant and rapid impact on their economic sustainability, even if those applications have obvious effects on the environmental or social bottom line. Moreover, empirical research has determined that the competitive advantage of going green has a significant influence on a company’s willingness to participate in green supply chain management practices (Caniëls, Cleophas, and Semeijn 2016). Thus, if implementations of Industry 4.0

technologies cannot be justified solely through an economic rationale, there may be a need for governmental bodies to establish incentive programs to facilitate a move towards greener operations.

This paper is limited in that the causalities between the three dimensions of sustainability were not directly addressed. In other words, the paper did not discuss the eventual negative impacts that could be caused to one or more of the dimensions of sustainability as the result of a directly positive impact to one. For a more comprehensive review of the sustainability of ETO supply chains, causal networks should be drawn to gain a holistic view of how increased sustainability in one dimension can affect the other dimensions.

Moreover, as we through a single case study investigate the shipbuilding industry specifically, the generalisability of this paper is limited. Although shipbuilding may be classified as an ETO industry, ETO companies can significantly differ from one another. Thus, in order to further generalise the paper's findings, we suggest similar studies about different ETO companies or multiple cases that compare ETO supply chains within different sectors in future research. More specifically, because shipyards and their operations play a vital role in the shipbuilding supply chain as a whole, more empirical evidence from a larger sample size could better guide the development of shipyards into the next generation of shipbuilding. For this purpose, and to continue the development of digital solutions that address the industrial challenges in shipbuilding, the authors' planned future research will aim to investigate multiple shipyards in a larger study.

7 Conclusions

In line with the concept of the triple bottom line, investigating the economic, environmental and social dimension of sustainability, this paper has highlighted several challenges in the shipbuilding industry and shows that challenges are present in all dimensions. Through a case study of a shipbuilding supply chain, this paper identifies sustainability challenges related to social performance (i.e., working conditions and supplier relationships and communications), environmental performance (i.e., emissions, the energy-efficiency of production and ship operations and end-of-life handling) and economic performance (i.e., productivity and cost-efficiency). From this, the paper adds a holistic perspective on sustainability to previous research that has investigated single dimensions more extensively (see e.g. Caniëls, Cleophas, and Semeijn (2016), Joe and Chang (2017), Li, Yi, and Zhang (2011), and Rahman and Karim (2015)). While sustainability challenges that are specifically related to the environment require additional research, the current paper intentionally addresses the larger picture of sustainability, an element which is critical for companies to move forward into the next generation of ETO manufacturing.

While previous research have offered generalised outlines for the potential application of Industry 4.0 technologies in shipbuilding supply chains (Ang et al. 2017), this paper contributes with more specificity to the operationalisation of a range of technological concepts. In this way, the current paper provides more substance to the adoption of Industry 4.0 technologies for shipbuilding and similar ETO industries. Moreover, the identification of existing challenges and application areas for Industry 4.0 technologies can further guide the development of digital solutions by making their utility and purpose more evident.

Even though the literature on the application of Industry 4.0 technologies in ETO remains scattered, unstructured and limited (Zennaro et al. 2019), several possible applications to address the challenges to sustainability have been identified. Nevertheless, because many of these involve pilot implementations or conceptual descriptions of possible applications that currently lack industrial implementation, more research is needed to further operationalise Industry 4.0 technologies and foster its adoption in ETO companies (see Fatorachian and Kazemi’s (2018) framework for operationalising Industry 4.0).

For practitioners, this paper provides further insight into the potential application areas for Industry 4.0 technologies. As the paper’s primary contribution, it presents nine different scenarios for how digitalisation can improve sustainability in shipbuilding. This, combined with existing general frameworks for the adoption of Industry 4.0 technologies, could prove useful for shipbuilding companies that wish to pursue improvements through digital solutions. For these implementations to be fully realised, clearer knowledge about the benefits of these technologies and descriptions of how they can be applied in specific contexts are essential. With its currently challenging market environment, these factors are particularly relevant to the shipbuilding industry.

Further research should address this paper’s limitations by investigating the causal relationships between sustainability dimensions in the shipbuilding industry, and by applying research methodologies that allow further generalisation of the findings of the current study.

Acknowledgements

We would like to thank all the participants that have been involved in the research and the different research projects that inspired this article.

Disclosure statement

No potential conflict of interest was reported by the authors.

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