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Doctoral thesis

Jo Wessel Strandhagen

Towards next-generation yard logistics

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
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Summary

Yards are industrial sites for production and servicing of ships and offshore maritime installations, such as oil and gas platforms and modules, offshore windmills, and fish farms—all essential products in the maritime industry. In recent years, both shipyards and offshore construction yards have experienced challenging market conditions. The global order book of new ships was in 2018 half the size of the peak year of 2008 (OECD, 2018). With a decreasing demand for new ships, the number of active yards globally has declined over the last decade (Danish Ship Finance, 2021). There is intense competition among the remaining yards, with many struggling to remain in business. Offshore construction yards have experienced a significant shift in demand from oil- and gas-related projects to projects related to renewable energy sources, such as offshore wind, which are characterized by significantly lower profit margins. Due to the current market situation, the importance of cost-efficiency has increased for both shipyards and offshore construction yards. This is particularly relevant in the Norwegian yard industry, characterized by high factor costs and a focus on providing high-value, customized, innovative products in low volumes. Accordingly, efforts are needed to ensure cost-efficient yard operations and strengthen the yards' economic sustainability.

One area with the potential to make an important contribution to cost-efficiency is logistics. Within the context of yards, this study defines yard logistics as *the coordination of the yard operations concerned with the flow of materials and information through the yard up to the production of the end product.* It entails the movement of the materials (components, parts, assemblies, and products), resources (including humans), and information required for producing and servicing large, complex, and customized products at a yard, and should be done with a minimum consumption of resources. In previous research, a holistic view on yard logistics has been lacking, and the range and diversity of different yard types have not been properly studied from a logistics perspective. Existing research on yard logistics has primarily targeted specific yard logistics problems, such as layout optimization and the movement of ship blocks in large-scale shipyards. There is a need for definitions, characterizations, and frameworks to move from anecdotal to scientific knowledge and to construct a holistic understanding of yard logistics. This study is motivated by that need—a prerequisite to develop effective logistics solutions.

In the current era of Industry 4.0, digitalization has emerged as a promising approach to realize performance improvements in industry. However, within the context of yards and other

engineer-to-order industries, the literature is scarce on specific applications of technologies to specific areas or processes. In particular, more research based on empirical investigations is needed to identify relevant application areas for digital technologies, in the yard logistics domain. A prerequisite for this digitalization is increased knowledge about yard logistics itself, including a deeper understanding of its constituents and characteristics. Awareness of the current logistics challenges is necessary to identify the applications of digital technologies that could actually address these challenges and thereby increase logistics performance. Therefore, the objective of this thesis was *to develop knowledge on yard logistics to improve yard logistics performance and identify how digitalization can support this improvement*. To this end, the following two research questions were defined:

1. *How can yard logistics be conceptualized?*

The first research question aimed to discover, develop, and structure knowledge on yard logistics. To examine this question, empirical data were collected through two multiple-case studies of three and eight yards, respectively, supported by reviews of the existing literature. From this, the question was answered by identifying characteristics and constituents of yard logistics, distinguishing between different types of yards and comparing them from a logistics perspective, including challenges. Furthermore, to provide an even more comprehensive understanding of yard logistics, yard logistics performance measurement and the factors affecting yard logistics were investigated. All this is necessary, fundamental knowledge to be able to develop efficient solutions for digitalized yard logistics.

2. *How can digital technologies be applied to contribute to more efficient yard logistics?*

The second research question aimed to explore digitalization in the yard logistics context. It originates from a multiple-case study investigating the contextual implications on the applicability of digital technologies in manufacturing logistics, which highlighted the need for context-specific studies. The question was further answered by identification of the required features of a digitalized yard logistics system and potential technologies, and by investigating, in a wider perspective, how digitalization can contribute to a sustainable yard industry. Finally, building on the developed knowledge, the answer to this research question culminates in a proposition of a concept for digitalized yard logistics, hence, the thesis has been titled "Towards next-generation yard logistics".

Case research is the main research method that was selected to answer these research questions and achieve the objective of the thesis. The research objective and questions are exploratory in nature, seeking to explore the particular context of yard logistics. To this end, a qualitative approach was taken. The case research in this thesis comprised five separate case studies—two single-case studies and three multiple-case studies—reported in the appended papers. Each case study had the same approach, aimed at collecting qualitative data on the cases through direct observations, semi-structured interviews, archival records, and existing documentation; then analyzing this data through qualitative data analysis methods in order to develop this thesis' research outcomes.

These outcomes, including their contributions to theory and implications for practice, can be summarized as follows:

Definition, characterization, constituents, and challenges of yard logistics. The empirical investigation related to research question 1, with support from the existing literature, is used to establish a definition of yard logistics as well as a description of its key characteristics. Furthermore, we define the constituents of yard logistics: products and materials; facilities, areas, and equipment; layout; material management; and work management. These constituents are further described according to a typology of yard operations, enabling comprehensive descriptions of the yard logistics of fabrication yards, outfitting yards, and service yards. We further identify and describe yard logistics challenges across these three yard types within the following areas: material reception, space and storage needs, warehouse management, material management, material handling, material flow, transportation, coordination, work management, walking time, information flow, and mobilization of human resources. These outcomes add to the knowledge on yard logistics and provide a foundation for practitioners to develop type-specific yard logistics solutions. Furthermore, the description of yard types can be used by practitioners to compare their yard against others by studying the commonalities and differences between them. This can facilitate learning and a deeper understanding of yard logistics.

Contextualization of performance measurement to yard logistics and a performance measurement system for yard logistics. We apply the theory of performance measurement to yard logistics and identify the aspects most relevant to yard logistics performance. Based on that we propose a set of performance measures for yard logistics as well as general guidelines for performance measurement system design, which can be used by practitioners to guide the development of yard-specific performance measurement systems.

Identification of factors affecting yard logistics. We identify four main factors affecting yard logistics: yard characteristics, product and market characteristics, process characteristics, and supply chain characteristics—each consisting of a set of variables that, together, describe a yard environment. A multiple-case study of three yards, mapped with regard to the four factors, illustrates the implications of these factors on yard logistics.

Insights into the context-dependency of the applicability of Industry 4.0 technologies. These results, based on a multiple-case study of four companies with different manufacturing environments, indicate that the applicability of Industry 4.0 technologies is affected by the degree of repetitiveness in the manufacturing environment. The main take-away is the need for company-specific approaches to digitalization—urging researchers and practitioners to develop yard-specific digitalization knowledge and solutions.

Outline of the potential impact of digitalization across entire supply chains in yard industries. By a case study of a shipbuilding supply chain, we identify both sustainability challenges as well as the digital solutions that can address the challenges. These results provide a wider perspective on the potential benefits of digitalization in the yard industry—valuable, complementary knowledge for practitioners of how digitalization efforts may offer benefits beyond yard logistics.

Identification of the features of digitalization that can address the main yard logistics challenges. Following a needs-based approach to digitalization, assessing the main yard logistics challenges, we identify and describe four features of digitalized yard logistics: a seamless, digitalized information flow; identification and interconnectivity; digitalized operator support; and automated and autonomous material flow. Each feature is linked to a yard logistics challenge and specifies what is needed in terms of digitalization to address this challenge. This knowledge helps practitioners to prioritize digitalization initiatives for solving targeted challenges.

Overview of the current state of digitalization in yard logistics. The current level of yard logistics digitalization is mapped and analyzed at eight yards by assessing their technology implementation level, digitalization strategy, digitalization resources and initiatives, and information technology (IT) system use and integration with respect to yard logistics. It provides a template for yards to make an initial assessment of their current digitalization level, which can support their further digitalization efforts.

Concept for digitalized yard logistics. The proposed concept describes and visualizes how the four features of digitalized yard logistics can be realized. It illustrates how digital technologies can be applied in specific areas of yard logistics and shows the possible effects on yard logistics performance. The concept may be used as inspiration for moving towards the next generation of yard logistics.

In conclusion, the thesis extends the knowledge in the field of yard logistics, giving the deeper understanding required for the development of cost-efficient solutions. It provides valuable insights on how digitalization may address current challenges and increase performance, thereby moving towards the next generation of yard logistics.

Sammendrag

Verft er industrielle områder for produksjon og service av skip og maritime offshore-installasjoner som olje- og gassplattformer og -moduler, offshore vindmøller og merder—essensielle produkter i maritim industri. I de siste årene har både skipsverft og offshoreverft opplevd utfordrende markedssituasjoner. Den globale ordreboken for nye skip var i 2018 halvparten av nivået i toppåret 2008 (OECD, 2018). Med synkende etterspørsel etter nye skip har også antallet verft globalt sunket det siste tiåret (Danish Ship Finance, 2021). Det er sterk konkurranse blant de gjenværende verftene, og mange sliter med å opprettholde virksomheten. Offshoreverft har opplevd betydelig endringer i etterspørsel—fra prosjekter for olje og gass til prosjekter knyttet til fornybare energikilder som offshore vind, hvor marginene er betydelig lavere. Med de nåværende markedssituasjonene har viktigheten av kostnadseffektivitet økt både for skipsverftene og offshoreverftene. Dette gjelder spesielt den norske verftsindustrien, karakterisert ved høye faktorkostnader og et fokus på å levere høyverdige, kundespesifikke, innovative produkter i lave volumer. Derfor må det tas grep for å sørge for kostnadseffektiv verftsdrift og en styrking av verftenes økonomiske bærekraft.

Ett område som kan være et viktig bidrag til kostnadseffektivitet er logistikk. Innenfor verftskonteksen definerer denne studien verftslogistikk som *koordinering av verftsdriften knyttet til material- og informasjonsflyten gjennom verftet frem til produksjonen av sluttproduktet.* Det innebærer forflytning av materialene (komponenter, deler, sammenstillinger og produkter), ressursene (inkludert arbeidsstokken) og informasjonen som trengs for produksjon og service av store, komplekse og kundespesifikke produkter ved et verft, og bør gjøres med et minimumsforbruk av ressurser. Tidligere forskning mangler et helhetlig syn på verftslogistikk og spekteret og mangfoldet av ulike verftstyper har ikke blitt tilstrekkelig dekkt fra et logistikkperspektiv. Eksisterende forskning på verftslogistikk har primært vært rettet mot spesifikke verftslogistikkproblemer, som optimalisering av layout og forflytning av skipsblokker ved store skipsverft. For å gå fra anekdotisk til vitenskapelig kunnskap er det behov for definisjoner, karakteristikker og rammeverk for å skape en helhetlig forståelse av verftslogistikk. Denne studien er motivert av dette behovet—en forutsetning for å utvikle effektive logistikkløsninger.

I dagens Industri 4.0-æra har digitalisering vist seg som en lovende tilnærming for å oppnå ytelsesforbedringer i industrien. For verft og andre engineer-to-order-bransjer er litteraturen mangelfull hva gjelder spesifikke anvendelser av teknologi for spesifikke områder eller

prosesser. Spesielt er det nødvendig med mer forskning basert på empiriske undersøkelser for å identifisere relevante bruksområder for digitale teknologier innen verftslogistikk. En forutsetning for denne digitaliseringen er økt kunnskap om verftslogistikk i seg selv, inkludert en dypere forståelse av dets bestanddeler og karakteristikker. Kjennskap til dagens logistikkutfordringer er nødvendig for å kunne identifisere de anvendelsene av digitale teknologier som faktisk kan adressere disse utfordringene, og med det øke logistikkytelsen. Formålet med denne avhandlingen er derfor *å utvikle kunnskap om verftslogistikk for å forbedre verftslogistikkytelsen og å identifisere hvordan digitalisering kan støtte en slik forbedring*. Til det formålet ble følgende to forskningsspørsmål formulert:

1. Hvordan kan verftslogistikk konseptualiseres?

Det første forskningsspørsmålet tok sikte på å oppdage, utvikle og strukturere kunnskap om verftslogistikk. For å besvare dette spørsmålet ble det samlet inn empirisk data gjennom to fler-case-studier av henholdsvis tre og åtte verft, støttet av gjennomganger av eksisterende litteratur. Fra dette ble forskningsspørsmålet besvart ved å identifisere karakteristikker og bestanddeler av verftslogistikk, skille mellom ulike typer verft og sammenligne dem fra et logistikkperspektiv, inkludert utfordringer. Videre, for å gi en enda mer helhetlig forståelse av verftslogistikk ble også ytelsesmåling og faktorene som påvirker verftslogistikk utforsket. Alt dette er nødvendig, grunnleggende forståelse for at man skal kunne utvikle gode og nyttige løsninger for digitalisering av verftslogistikk.

2. Hvordan kan digitale teknologier anvendes for å bidra til mer effektiv verftslogistikk?

Det andre forskningsspørsmålet tok sikte på å utforske digitalisering i verftslogistikksammenheng. Det stammer fra en fler-case-studie som undersøker de kontekstuelle implikasjonene for anvendeligheten av digitale teknologier i produksjonslogistikk, som fremhevet behovet for kontekstspesifikke studier. Spørsmålet ble videre besvart ved å identifisere de nødvendige egenskapene til et digitalisert verftslogistikksystem og potensielle teknologier, og ved å undersøke, i et bredere perspektiv, hvordan digitalisering kan bidra til en bærekraftig verftsindustri. Til slutt, basert på den utviklede kunnskapen, kulminerer svaret på dette forskningsspørsmålet i et forslag til et konsept for digitalisert verftslogistikk, og derfor har oppgaven fått tittelen «Mot neste generasjons verftslogistikk».

Case-forskning er hovedforskningsmetoden som ble valgt for å besvare disse forskningsspørsmålene og nå formålet med oppgaven. Formålet og forskningsspørsmålene er utforskende av natur, og søker å utforske den spesifikke konteksten verftslogistikk. Til dette ble det tatt en kvalitativ tilnærming. Case-forskningen i denne oppgaven omfatter fem separate case-studier—to enkelt-case-studier og tre fler-case-studier. Hver case-studie hadde den samme tilnærmingen, rettet mot å samle inn kvalitative data om casene gjennom direkte observasjoner, semistrukturerte intervjuer, arkivdokumenter og eksisterende dokumentasjon, for så å analysere dataene gjennom kvalitative analysemetoder for å utvikle avhandlingens forskningsresultater.

Disse forskningsresultatene, inkludert deres teoretiske bidrag og innvirkning på praksis, kan oppsummeres som følger:

Definisjon, karakterisering og bestanddeler av, samt utfordringer ved, verftslogistikk.. De empiriske undersøkelsene knyttet til forskningsspørsmål 1, støttet av eksisterende litteratur, brukes for å etablere en definisjon på verftslogistikk, samt en beskrivelse av dets nøkkelkarakteristikker. Videre definerer vi verftslogistikk sine bestanddeler: produkter og materialer; fasiliteter, områder og utstyr; layout; materialstyring og arbeidsledelse. Disse bestanddelene er videre beskrevet i henhold til en typologi for verftsdrift og muliggjør omfattende beskrivelser av verftslogistikk ved fabrikasjonsverft, utrustningsverft og serviceverft. Videre identifiserer og beskriver vi verftslogistikkutfordringer på tvers av disse tre verftstypene innenfor de følgende områdene: materialmottak, areal- og lagringsbehov, lagerstyring, materialstyring, materialhåndtering, materialflyt, transport, koordinering, arbeidsledelse, gangtid, informasjonsflyt og mobilisering av menneskelige ressurser. Disse resultatene gir økt kunnskap om verftslogistikk og et grunnlag for praktikere for å kunne utvikle typespesifikke verftslogistikkløsninger. Videre kan beskrivelsene av verftstyper benyttes av praktikere til å sammenligne verft ved å undersøke likheter og forskjeller. Dette kan bidra til læring og en dypere forståelse av verftslogistikk.

Kontekstualisering av ytelsesmåling til verftslogistikk og et ytelsesmålingssystem for verftslogistikk. Vi anvender teori om ytelsesmåling på verftslogistikk og identifiserer de mest relevante aspektene ved verftslogistikkytelse. Basert på dette foreslår vi et sett med ytelsesmål for verftslogistikk, samt generelle retningslinjer for design av ytelsesmålesystem som kan benyttes av praktikere som veiledning for utvikling av verftsspesifikke ytelsesmålesystemer.

Identifisering av faktorene som påvirker verftslogistikk. Vi identifiserer fire hovedfaktorer som påvirker verftslogistikk: verftskarakteristikker, produkt- og markedskarakteristikker, prosesskarakteristikker og verdikjedekarakteristikker—hver bestående av et sett variabler som sammen beskriver et verftsmiljø. En fler-casestudie av tre verft, kartlagt i henhold til de fire faktorene, illustrerer innvirkningen faktorene har på verftslogistikk.

Innsikt i avhengigheten mellom Industri 4.0-anvendbarhet og produksjonsmiljøer. Disse resultatene, basert på en fler-case-studie av fire bedrifter med ulike produksjonsmiljøer, indikerer at anvendbarheten av Industri 4.0-teknologier påvirkes av graden av gjentagelse i produksjonsmiljøet. Den viktigste innsikten er behovet for bedriftsspesifikke tilnærminger til digitalisering, som oppfordrer forskere og praktikere til å identifisere kunnskap og løsninger verftsspesifikk digitaliseringskunnskap og -løsninger.

Oversikt over den potensielle effekten av digitalisering på tvers av hele verdikjeder innenfor verftsindustri. Gjennom en case-studie av en verdikjede for skipsbygging identifiserer vi utfordringer knyttet til bærekraft og de digitale løsningene som kan adressere disse utfordringene. Disse resultatene gir et bredere perspektiv på de potensielle gevinstene ved digitalisering av verftsindustrien—verdifull, komplementær kunnskap for praktikere om hvordan digitaliseringsinitiativer kan gi gevinster også utover verftslogistikk.

Identifisering av de egenskapene ved digitalisering som kan adressere hovedutfordringene i verftslogistikk. Gjennom en behovsbasert tilnærming til digitalisering, med undersøkelser av hovedutfordringene knyttet til verftslogistikk, identifiserer og beskriver vi fire egenskaper ved digitalisert verftslogistikk: sømløs, digitalisert informasjonsflyt; identifisering og sammenkobling; digitalisert operatørstøtte; og automatisert og autonom materialflyt. Hver egenskap er koblet til en verftslogistikkutfordring og spesifiserer hva som kreves med hensyn på digitalisering for å adressere denne utfordringen. Denne kunnskapen hjelper praktikere til å prioritere digitaliseringsinitiativer for å løse bestemte utfordringer.

Oversikt over dagens digitalisering av verftslogistikk. Det nåværende nivået for digitalisering av verftslogistikk kartlegges og analyseres ved åtte verft ved å vurdere deres teknologiimplementeringsnivå, digitaliseringsstrategi, digitaliseringsressurser og -initiativer, og bruk og integrasjon IT-systemer knyttet til verftslogistikk. Det gir en mal for verft til å gjøre innledende vurderinger av deres nåværende digitaliseringsnivå, som kan støtte deres videre digitaliseringsinitiativer.

Konsept for digitalisert verftslogistikk. Det foreslåtte konseptet beskriver og illustrerer hvordan de fire egenskapene ved digitalisert verftslogistikk kan realiseres. Det illustrerer hvordan digitale teknologier kan anvendes på spesifikke områder innenfor verftslogistikk og viser de mulige effektene på verftslogistikkytelse. Konseptet kan brukes som inspirasjon på veien mot neste generasjons verftslogistikk.

For å konkludere så utvider denne avhandlingen kunnskapen om verftslogistikk og gir den dypere forståelsen som kreves for å kunne utvikle kostnadseffektive løsninger. Den gir verdifull innsikt i hvordan digitalisering kan løse dagens utfordringer og øke ytelse, og dermed ta oss mot neste generasjons verftslogistikk.

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Somehow, I ended up walking in the footsteps of my two academic parents, who would have thought? I express my deepest gratitude to them, Helle and Ola (a second mention for you, then), and to my brother Peter. I have felt your wholehearted admiration and pride along the way, and your support and inspiration are priceless. I cannot thank you enough.

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Trondheim, July 2022
Jo Wessel Strandhagen

List of abbreviations

AGV	Automated guided vehicle
AI	Artificial intelligence
AMR	Autonomous mobile robot
AR	Augmented reality
ATO	Assemble-to-order
BOM	Bill of materials
CAD	Computer-aided design
COBOT	Collaborative robot
CODP	Customer order decoupling point
CPS	Cyber-physical system
DSR	Design science research
EPC	Engineering, procurement, and construction
ERP	Enterprise resource planning
ETO	Engineer-to-order
HVAC	Heating, ventilation, and air conditioning
IoS	Internet of Services
IoT	Internet of Things
IT	Information technology
MES	Manufacturing execution system
MTO	Make-to-order
MTS	Make-to-stock
PLM	Product lifecycle management
PAC	Production activity control
PPC	Production planning and control
RFID	Radio frequency identification
RQ	Research question
TRL	Technology readiness level
VR	Virtual reality
VSM	Value stream mapping

List of appended papers and declaration of authorship

Paper	Title	Declaration of authorship
1	Strandhagen, J. W., Semini, M. & Alfnes, E. (2022). Yard logistics: Characteristics and challenges. Submitted to the *International Journal of Production Research.*	Strandhagen conceptualized the paper and collected data with Semini and Alfnes. Strandhagen wrote the paper with feedback from Semini and Alfnes.
2	Strandhagen, J. W., Andersen, B., Semini, M. & Alfnes, E. (2022). Performance measurement in engineer-to-order yard logistics. Submitted to the *International Journal of Productivity and Performance Management.*	Strandhagen conceptualized the paper and collected data with Semini and Alfnes. Strandhagen wrote the paper with feedback from Andersen, Semini, and Alfnes.
3	Strandhagen, J. W., Jeong, Y., Woo, J. H., Semini, M., Wiktorsson, M., Strandhagen, J. O. & Alfnes, E. (2020). Factors affecting shipyard operations and logistics: A framework and comparison of shipbuilding approaches. In: B. Lalic, V. Majstorovic, U. Marjanovic, G. von Cieminski, & D. Romero (Eds.) *Advances in Production Management Systems. Towards Smart and Digital Manufacturing. APMS 2020. IFIP Advances in Information and Communication Technology* (Vol. 592, pp 529-537): Springer.	J. W. Strandhagen and Jeong conceptualized the paper and collected data with Woo and Semini. Strandhagen and Jeong wrote the paper with feedback from Woo, Semini, Wiktorsson, J. O. Strandhagen, and Alfnes.
4	Strandhagen, J. W., Alfnes, E., Strandhagen, J. O. & Vallandingham, L. R. (2017). The fit of Industry 4.0 applications in manufacturing logistics: A multiple case study. *Advances in Manufacturing*, 5, 344-358.	J. W. Strandhagen conceptualized the paper and collected the data with support from Alfnes. J. W. Strandhagen wrote the paper with input from Vallandingham and feedback from Alfnes and J. O. Strandhagen.
5	Strandhagen, J. W., Buer, S.-V., Semini, M., Alfnes, E. & Strandhagen, J. O. (2020). Sustainability challenges and how Industry 4.0 technologies can address them: A case study of a shipbuilding supply chain. *Production Planning & Control*, 1-16.	J. W. Strandhagen conceptualized the paper and collected the data with Semini. J. W. Strandhagen wrote the paper with feedback from Buer, Semini, Alfnes, and J. O. Strandhagen.
6	Strandhagen, J. W., Buer, S. V., Semini, M. & Alfnes, E. (2019). Digitalized manufacturing logistics in engineer-to-order operations. In F. Ameri, K. Stecke, G. von Cieminski, & D. Kiritsis (Eds.), *Advances in Production Management Systems. Production Management for the Factory of the Future. APMS 2019. IFIP Advances in Information and Communication Technology* (Vol. 566, pp. 579-587): Springer.	Strandhagen conceptualized the paper and collected the data with Semini. Strandhagen wrote the paper with feedback from Buer, Semini, and Alfnes.

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1 Introduction

This chapter introduces this research study of yard logistics. It presents the background for the study, including the relevant industrial challenges of today and my personal interest in the topic. Then, based on a review of the state-of-the-art, it describes the research motivation for the study before it presents the research objective and research questions. Further, it defines the research scope, and, finally, the chapter ends with an outline of the thesis.

1.1 Background

Yards are essential actors in the broadly defined maritime industry. They are responsible for the fabrication, assembly, outfitting, and after-sales service of ships and offshore products, such as oil platforms and modules, offshore windmills, and fish farms—key products in a range of different maritime supply chains. Based on the products delivered by the yards, we can distinguish between yards within shipbuilding and yards within offshore construction.

Shipbuilding companies across the world have been operating in a challenging market environment for several years, with an order book in 2018 that was half the size of its peak in 2008 (OECD, 2018). The reduced demand has intensified global competition, as there are fewer shipbuilding projects for shipyards to compete for. In Norwegian shipbuilding, an important factor contributing to the challenging market environment was the drastic reduction in the price of oil around 2015, which led to a significant reduction in the demand for new ships for the oil and gas industry (Menon Economics, 2019). Although oil prices have been recently recovering, the demand for these ships has not—due to lots of ships still being laid up and that Asian yards now are taking most of the new orders (Shipyards' & Maritime Equipment Association of Europe [SEA Europe], 2020). For Norwegian yards as well as many comparable European actors there is an increasing competition from Asian shipbuilders, which benefit from lower factor costs and stronger governmental support. This has forced the Norwegian shipyards to transition from the oil and gas market to alternative markets, often with lower margins—a tremendous challenge in today’s shipbuilding industry. A similar dynamic can be seen in offshore construction yards, which have been experiencing a declining demand for oil- and gas-related constructions, such as oil platforms. Thus, they are seeking alternative ways to maintain business performance, and for many, to stay in business. Furthermore, the increasingly stringent requirements to reduce the environmental impact of new products also affects operations. Accordingly, many yards are adjusting to the new market situation. Considering the inevitable need to move from the oil and gas industry towards a greener global industry, markets such as offshore wind energy are now emerging for the yards. For shipyards, this entails construction and service vessels for offshore wind projects, while offshore construction yards can utilize their facilities, competence, and knowledge to deliver platforms, structures, and substructures for such projects. Existing yards hold much of the facilities, competence, and knowledge needed to develop products for such markets, and this represents an opportunity for many of them to maintain and strengthen their operations in the coming years. However, the transition also involves significant challenges for the yards as they adapt their yard operations to be able to deliver different products. This, in addition to the lowered global demand, and increasing competition from regions with lower factor costs and stronger governmental support, which has led to a price drop, has put the yards under a significant amount of pressure to improve their economic sustainability so that they can remain in business.

From an operations management point of view, the key challenge involves cost-efficient operations. Operations management is "the activity of managing the resources that create and deliver services and products" (Slack & Brandon-Jones, 2019, p. 6), and can make a significant contribution to economic sustainability. Yard operations, that is, operations management at yards, is here used as an umbrella term for all physical and administrative tasks performed as a part of the production process at a yard. Exactly tasks are carried out and how may differ from yard to yard, depending on which products they produce and which markets they serve. This thesis focuses on logistics, an important element of operations management. It can be described as the science of efficient flow of materials and concerns all the activities that ensure that materials and products are at the right place at the right time (Jonsson, 2008). Logistics has been emphasized to have a significant effect on cost-efficiency (Christopher, 2011) and can, thus, play an important role for yards in their efforts to stay in business. A yard can be viewed as a logistics system, with the goal of ensuring an efficient flow of materials supported by an efficient flow of information, with a minimum consumption of resources, and we can define yard logistics as *the coordination of the yard operations concerned with the flow of materials and information through the yard up to the production of the end product.* The question is, how can yard operations be coordinated to increase the efficiency of the yard's internal material flow—and thereby to increase the efficiency of yard logistics and enable more cost-efficient yard operations?

Yard operations can be classified as engineer-to-order (ETO) manufacturing operations. With the ETO manufacturing approach, some design and engineering as well as purchasing and physical production are performed after a customer order has been contracted (Gosling & Naim, 2009). ETO manufacturing is sometimes called one-of-a-kind manufacturing, as products that are designed and engineered based on a specific customer order are often the only ones of their kind. The implications for the manufacturer, or the yard, is that, since every product is designed and engineered based on the customer's requirements, it will never make a product in exactly the same way again. This has major implications for internal logistics, as it creates a dynamic, uncertain, and complex manufacturing environment (Bertrand & Muntslag, 1993). These characteristics distinguish this type of manufacturing environment from more repetitive manufacturing environments. The need for coordination of material and information flows is critical (Mello et al., 2017), as tailored approaches are required for effective and efficient management of manufacturing operations (Adrodegari et al., 2015). However, there is a lack of logistics solutions that fit the ETO context (Zennaro et al., 2019).

With the fourth industrial revolution, Industry 4.0, the manufacturing industry is expected to change. New technologies will enable more efficient processes, smart products and services, as well as new business models (OECD, 2017). This will be enabled by the base technologies Internet of Things (IoT), cloud computing, Big Data, and analytics (Frank et al., 2019). Building on these technologies, Industry 4.0 offers cyber-physical systems (CPS) that link the physical and the digital worlds—connecting infrastructure, physical objects, humans, machines, and processes in the industrial context—thereby creating seamless, real-time controlled industrial manufacturing environments (Zheng et al., 2021). While there is a tremendous technology push, with rapid technological advancements, there is also a strong demand for new technological solutions in industry. In particular, manufacturers in high labor cost countries like Norway see an opportunity to maintain their competitiveness—despite high labor costs—by exploiting new technologies. Research on Industry 4.0 related to the ETO context has received growing attention, although it is still in an early phase (Cannas & Gosling, 2021; Zennaro et al., 2019). Moreover, research on the application of Industry 4.0 to manufacturing logistics indicates that new digital technologies are easier to apply in companies in which the repetitiveness is high (Strandhagen et al., 2017). For less repetitive environments, such as yards and other types of ETO environments, application of digital technologies seems more difficult. The high complexity, uncertainty, and dynamism created by the characteristics of the ETO environment are believed to be key factors affecting the applicability of digital technologies. On the other hand, the potential for improvement if digital technologies are successfully adapted and applied should be correspondingly large, as complexity and dynamism are exactly what digitalization is expected to manage more efficiently. Accordingly, digitalization is expected to be a promising approach and enabler of improved yard logistics performance. However, it is still not clear how digital technologies can and should be applied in yard logistics.

The Production Management research group of the Department of Mechanical and Industrial Engineering at NTNU has been at the forefront of research on customized production for more than a decade. The group's strategic focus on this vitally important field within industrial production in Norway led to the scholarship that enabled this research. The competence and research culture of the Production Management research group aligned with my own fascination for the Norwegian yard industry, with its strong traditions and importance with regard to value creation—built on engineering highly innovative and customized products. With manufacturing logistics as my field of expertise, yard logistics emerged as the perfect topic.

Therefore, this study will investigate yards as logistics systems by analyzing the constituents, characteristics, and challenges of yard logistics. The main idea is that discovering, developing, and structuring this knowledge will enable the development of the necessary, tailored logistics solutions for enhancing yard logistics performance. Building on this enhanced knowledge, the study will further investigate how digital technologies can be adapted and applied to move towards the next generation of yard logistics.

1.2 Research motivation

ETO manufacturing environments, such as yards, have a range of characteristics that differentiate them from other types of manufacturing environments. ETO products are typically complex, have deep product structures, and are highly customized (Hicks et al., 2000). The high level of customization makes the repetitiveness of production and logistics low (MacCarthy & Fernandes, 2000). This includes the flow of material, process routings, and lead times, which may vary greatly between each product, part, or component. Moreover, ETO manufacturing is characterized by a dynamic and uncertain market situation, with high fluctuations in product mix and sales volume, making it challenging to predict future demand (Bertrand & Muntslag, 1993). Complexity and dynamism are considered intrinsic features in the ETO business environment, and it is important to understand and manage them better

(Birkie & Trucco, 2016). Several studies have examined the effects and implications of contextual factors of complexity and dynamism (Azadegan et al., 2013; Browning & Heath, 2009; Dess & Beard, 1984; Duncan, 1972; Sousa & Voss, 2001; Swamidass & Newell, 1987; Wong et al., 2011; Zhang et al., 2012). Birkie and Trucco (2016) looked at these in the ETO context, studying their influence on lean practices. However, there is a lack of research on such factors and their implications from a logistics point of view.

Within the ETO sector as a whole, there is research on logistics. Bortolini et al. (2019) studied logistics planning and control with empirical data from a construction site and proposed a logistics planning and control model. Carvalho et al. (2016) proposed and applied a model for capacity planning in the ETO production of high pressure boilers and reactors. Mourtzis et al. (2016) investigated the challenge of complexity in ETO manufacturing and proposed a short-term scheduling mechanism based on a case study from the mold-making industry. Ghiyasinasab et al. (2021) proposed production planning models for the prefabrication of ETO parts in construction. Dal Borgo and Meneghetti (2019) studied the ETO aspects of production planning in curtain wall production. Telles et al. (2020) investigated the application of drum–buffer–rope in the ETO production lines of an aerospace manufacturer. Various other studies have also addressed challenges related to logistics in different ETO cases (see e.g., Dallasega and Rauch (2017), Matt (2014), and Seth et al. (2017)).

While research in the ETO field has advanced over the last decade, it is mainly focused on other types of ETO manufacturing and supply chains than yards (Cannas & Gosling, 2021). Furthermore, the existing typologies and taxonomies of ETO companies and products often lack yards or the products produced at yards (see e.g., Willner et al. (2016) or Amaro et al. (1999)). Hicks et al. (2001) included an offshore construction company in their empirical study, although their research focused on vertical integration rather than on logistics.

Research on ETO has not sufficiently focused on the important context of yards. The previously outlined challenges in the yard industry require more targeted research, which also would extend ETO knowledge and theory. A certain portion of the research on shipbuilding has been conducted on the supply chain level, addressing topics such as supply chain coordination (Mello et al., 2017) and supply chain planning (Nam et al., 2018). Other studies have been positioned on a more strategic level, addressing offshoring strategies (Semini et al., 2018) and strategies for customization (Semini et al., 2014). The literature on offshore construction typically emphasizes design, mechanical properties, and the physical production process, giving little attention to the internal logistics at the offshore construction yards (El-Reedy, 2020). Overall, the current research on yard logistics is both limited and scattered. It is typically focused on large-scale shipyards and centers around problems related to ship block logistics and their spatial arrangement at yards with a high amount of parallel shipbuilding projects (Jeong et al., 2018b; Kim et al., 2020), or higher level planning (Ju et al., 2020; Lee et al., 2018). Few studies have addressed the outfitting stage (Rose et al., 2016), i.e., the installation of pipes and machinery; cabling and electrical systems; heating, ventilation, and air conditioning (HVAC); and accommodation and hotel functions (Semini et al. 2018), and repair operations (Mourtzis, 2005) from a logistics perspective. For Norwegian yards, it is the logistics related to such operations that is the most relevant issue. Existing research has not properly covered the range and diversity of maritime yards in the ETO context or the internal logistics of these yards. Studies have mainly addressed specific problems at specific types of yards. Thus, holistic and structured knowledge on yard logistics is missing. This study is motivated by the need for a deeper understanding of the yard logistics system, seeking to facilitate the further development of effective logistics solutions, principles, and methods for yards.

Digitalization and the technologies within Industry 4.0 are expected to cause disruptive changes in manufacturing, and it includes several technological advances that can have a significant impact on manufacturing logistics. Research on digitalization and Industry 4.0 has accelerated rapidly in recent years. However, research on the actual application of digital technologies in manufacturing is still lacking (Zheng et al., 2021). Studies have mainly focused on universal assessments of digitalization of manufacturing. While that has been a necessary step, there is now a need for investigations on how these technologies can be applied in different contexts.

There is currently an emerging research stream on Industry 4.0 in ETO (Cannas & Gosling, 2021), and research on the application of Industry 4.0 technologies in the specific context of ETO manufacturing is seen as a central part of future research in the field (Zennaro et al., 2019). Nevertheless, existing research has considered only a limited number of specific, technological applications for specific areas or processes in yard operations. The digitalization of yard logistics is still at a superficial level, and more empirically based research is required to identify the most relevant application areas. Moreover, the successful digitalization of yard logistics requires structured knowledge and descriptions of the yard logistics system, including its constituents and characteristics. For digital technologies to increase efficiency and logistics performance, more knowledge is also needed regarding the current challenges experienced in different types of yards.

1.3 Research objective and questions

To address the research challenges described above, the main research objective of this study is to develop knowledge on yard logistics needed to improve yard logistics performance and identify how digitalization can support this improvement.

Accordingly, the following two research questions (RQs) are formulated:

RQ1: How can yard logistics be conceptualized?

The first research question aims to discover, develop, and structure knowledge on yard logistics. It seeks to conceptualize yard logistics by defining and describing it, identifying its key characteristics, main constituents, and challenges, including differences between different types of yards. To provide an even more holistic understanding of yard logistics, the question also aims to contextualize performance measurement to yard logistics and investigate the factors affecting yard logistics. This fundamental knowledge is considered necessary to be able to develop efficient logistics solutions that increase cost-efficiency, and to develop efficient solutions for digitalized yard logistics.

RQ2: How can digital technologies be applied to contribute to more efficient yard logistics?

The second research question aims to explore digitalization in the yard logistics context. The question seeks to investigate the contextual implications on the applicability of digital technologies in this context. Further, the question aims to identify which features are required in a digitalized yard logistics system, and the technologies that can provide those features. To emphasize the wide potential of digitalization, the question also investigates digitalization from a wider perspective on the yard industry. Finally, the knowledge generated is synthetized, enabling the development of a concept for digitalized yard logistics and an assessment of the potential effects of digitalization on yard logistics performance.

1.4 Research scope

This study lies within the field of production management, which comprehends operations management within industrial production contexts. The general units of analysis are industrial production sites, and the particular industrial production sites targeted in the study are yards.

Yards, as defined in this study, are industrial sites for production and servicing of ships (shipyards) and offshore maritime installations (offshore construction yards). They are facilities used for the production and service of large, complex, and customized products. With this focus, the industrial production context targeted in this study is ETO manufacturing, which is the approach followed by yards producing or servicing customized products that are designed and engineered based on specific customer requirements. The definition of yards in this study excludes some yards, such as container yards, various types of stock yards, log yards, and slab yards. They are excluded because they are operating in other contexts. The study is targeted towards yards producing and servicing ships and offshore maritime constructions, such as oil and gas platforms and modules, offshore windmills, and fish farms. Nevertheless, the peculiarities and distinct characteristics of the ETO approach are also relevant outside the yard context in industries with similar characteristics, such as the construction industry, although that topic is beyond the scope of this study.

Furthermore, the study lies within the field of logistics. Logistics is a broad field, here narrowed down to internal logistics, which refers to the logistics within the physical boundaries of a site or facility (Gudehus & Kotzab, 2012). Applied to a manufacturing context, we find manufacturing logistics, which "deals with the coordination of the operations related to the flow of materials through the manufacturing departments up to the production of the end product" (Caron & Fiore, 1995, p. 315). This flow of materials is directly linked to the flow of information (Jonsson, 2008). Accordingly, manufacturing logistics, as it is considered in this study, is concerned with managing the flows of both material and information that are required for the production of a product at a site. The study only includes the internal logistics and adopts a "door-to-door" approach, following products from when they enter the production site until they exit or can be considered ready for exiting. However, the various interfaces between the logistics system and suppliers, customers, and other company-internal systems are highly relevant and are therefore also considered in the study. Furthermore, the study takes an operative perspective, as opposed to a strategic or tactical perspective, focusing on the execution of operative tasks in a logistics system. Planning and scheduling of production, including any short-term replanning and rescheduling, are considered as tasks providing *input* to the logistics system and specifying the requirements the logistics system has to fulfil. Humans are indeed elements in the logistics system, and within the scope of the study in that broad sense. However, the study does not consider human factors, such as physical, mental, or perceptual aspects (Vijayakumar et al., 2022).

While digitalization is a general term, describing the use of digital technology in the whole range of areas in society, in this study it is specifically applied to the manufacturing logistics context. Industry 4.0 is often referred to when addressing the digitalization of industry, and these two terms are used interchangeably in this thesis. With the scope narrowed down to internal logistics, this study focuses on the aspects of Industry 4.0 that can impact internal logistics. The approach to Industry 4.0 in this study is needs-oriented, meaning that the various elements and technologies within Industry 4.0 will be investigated based on identified needs and challenges in the internal logistics context the study targets. Moreover, this study concentrates on the application of technology. This means that neither the technical aspects of the various technologies nor their implementation process are in this thesis' focus.

The contextual factors that are considered in this study are related to what is called the manufacturing environment. These are factors related to the product, market, and production process (Buer et al., 2018b). Accordingly, yards are investigated in light of their product characteristics, important aspects of the markets they produce for, and their internal production process. Furthermore, the study is targeted towards the mentioned, current challenges of the Norwegian yard industry, characterized by high factor costs and where the yards are typically:

- Not able to compete in the high-volume production of more standardized products.
- Focusing on providing high-value, customized, innovative products through high flexibility.
- Focusing on technologically advanced operations, such as outfitting, commissioning, assembly of large, heavy objects, and advanced after-sales service operations.

Meanwhile, in countries with lower labor costs, there is a larger proportion of yards producing higher volumes of more standardized products, without the same focus on customization, innovativeness, and flexibility in their operations, and their challenges might deviate from those of the Norwegian yards.

1.5 Thesis outline

The thesis consists of two parts. Part I is the main report, while Part II is the collection of papers. Part I is organized as follows:

Chapter 1 is the introductory chapter. It provides the background and research motivation for the study and introduces the main fields of research covered. Following that, the chapter presents the main research objective and research questions, the study's research scope, and the structure of this thesis.

Chapter 2 covers the theoretical background of the main topics related to this study. It frames the study within the main topics of logistics in manufacturing, ETO manufacturing, and digitalization. The chapter also reviews existing literature on logistics and digitalization in yard operations, specifically, and ends with a presentation of the key constructs of the study and its research framework.

Chapter 3 presents the research design of the study. Building on the research objective and questions, this chapter describes the overall research methodology of the study and how case research was used as the research method. Furthermore, the chapter explains how research quality has been ensured.

Chapter 4 presents the research results. It summarizes the results from each of the appended papers and establishes the link between them to answer the research questions.

Chapter 5 contains a discussion of the study's results. The chapter first revisits the research questions and then provides a general discussion of the results and how they link to the existing literature. It should be emphasized that this chapter is intended to give only general reflections on the results. The results are discussed in more detail in the papers in Part II.

Chapter 6 is the conclusion of this thesis. It summarizes the study, provides some concluding remarks, and presents the study's contributions to theory and implications for practice. Finally, it highlights the limitations of the study and provides recommendations for further research.

Part II contains the following six papers, which have been written to disseminate the results of the study:

1. Strandhagen, J. W., Semini, M. & Alfnes, E. (2022). Yard logistics: Characteristics and challenges. Submitted to the *International Journal of Production Research*.
2. Strandhagen, J. W., Andersen, B., Semini, M. & Alfnes, E. (2022). Performance measurement in engineer-to-order yard logistics. Submitted to the *International Journal of Productivity and Performance Management*.
3. Strandhagen, J. W., Jeong, Y., Woo, J. H., Semini, M., Wiktorsson, M., Strandhagen, J. O. & Alfnes, E. (2020). Factors affecting shipyard operations and logistics: A framework and comparison of shipbuilding approaches. In: B. Lalic, V. Majstorovic, U. Marjanovic, G. von Cieminski, & D. Romero (Eds.) *Advances in Production*

Management Systems. Towards Smart and Digital Manufacturing. APMS 2020. IFIP Advances in Information and Communication Technology (Vol. 592, pp 529-537): Springer.

4. Strandhagen, J. W., Alfnes, E., Strandhagen, J. O. & Vallandingham, L. R. (2017). The fit of Industry 4.0 applications in manufacturing logistics: A multiple case study. *Advances in Manufacturing*, 5, 344-358.
5. Strandhagen, J. W., Buer, S.-V., Semini, M., Alfnes, E. & Strandhagen, J. O. (2020). Sustainability challenges and how Industry 4.0 technologies can address them: A case study of a shipbuilding supply chain. *Production Planning & Control*, 1-16.
6. Strandhagen, J. W., Buer, S. V., Semini, M. & Alfnes, E. (2019). Digitalized manufacturing logistics in engineer-to-order operations. In F. Ameri, K. Stecke, G. von Cieminski, & D. Kiritsis (Eds.), *Advances in Production Management Systems. Production Management for the Factory of the Future. APMS 2019. IFIP Advances in Information and Communication Technology* (Vol. 566, pp. 579-587): Springer.

2 Theoretical background

This chapter presents the theoretical background of the three main domains related to this study. These are presented in the first three sections of this chapter. Then, the chapter reviews existing literature related to the more specific topics of logistics and digitalization in yard operations. The chapter ends with a presentation of the key constructs of the study and its research framework.

Based on the background, research motivation, objective, questions, and scope of this research, presented in Chapter 1, three main domains are considered in this research. The field of interest for this study is logistics—specifically logistics in manufacturing—which, therefore, is the first main domain covered in this chapter. Further, the research is targeted towards an industrial context that is commonly referred to as ETO manufacturing, comprising the industrial production at yards. Then, as the research seeks to investigate the application of digital technologies, digitalization is covered as the third main domain in this chapter. These three main domains are then integrated in section 2.4, presenting logistics and digitalization in yard operations. Finally, the key constructs and research framework, which have been defined and developed based on theory are presented and explained.

2.1 Logistics in manufacturing

Logistics in the manufacturing context can be defined as "the art and science of obtaining, producing, and distributing material and product in the proper place and in proper quantities" (APICS). Its general purpose or task is often referred to as the four rights of logistics: "Logistics has to provide the right quantities of goods most efficiently at the right place in the right order within the right time" (Gudehus & Kotzab, 2012, p. 3). While these definitions explicitly connect logistics to the efficient flow of material, the efficient flow of information is a critical condition to achieve this (Jonsson, 2008).

While the history of logistics is long, the underlying principles of effective material flow remain firmly established and have broad, general applicability (Christopher, 2011; Gudehus & Kotzab, 2012). It has been practiced as isolated tasks, such as conveying, lifting, and transport; buffering and storing; handling, packing, and stacking; and carrying, shipping, and traveling. The integration of such tasks and attention to their management led to the development of the field of logistics (Gudehus & Kotzab, 2012). Logistics have long played a critical role in society. However, the view of logistics as a source of competitive advantage is more recent (Christopher, 2011). The importance of logistics is reflected by its influence on customer service, cost, flexibility, tied-up capital, time, and the environment (Jonsson, 2008). In this way, logistics influence the bottom line of companies, with the potential to improve the return on investment or return on capital employed (Christopher, 2011; Jonsson, 2008).

Logistics is relevant in a range of areas within industry, including manufacturing. Manufacturing logistics, or production logistics, concern the control of materials, information, and resources in a manufacturing company (Strandhagen et al., 2021) and is used as a broad term for logistics in the manufacturing or production context. It "deals with the coordination of the operations related to the flow of materials through the manufacturing departments up to the completion of the end product" (Caron & Fiore, 1995, p. 315). Logistics can be viewed from different perspectives, both with regard to time (strategic, tactical, and operative perspectives) and the limits of the logistics system (internal, external, and network perspectives) (Jonsson, 2008). The focus in this thesis is on the execution of operative tasks in a logistics system which aim to ensure performance in terms of order fulfillment, throughput, storage, and delivery time; quality in terms of availability, due date reliability, consignment quality, and flexibility; and minimal costs related to personnel, resources, transport, and inventory (Gudehus & Kotzab, 2012).

Figure 1 shows a logistics system from an individual company's perspective (i.e., with an internal perspective of the logistics system). It illustrates the focus on the flow of material through the system while also emphasizing the role of information flow through coordination and control of the logistics.

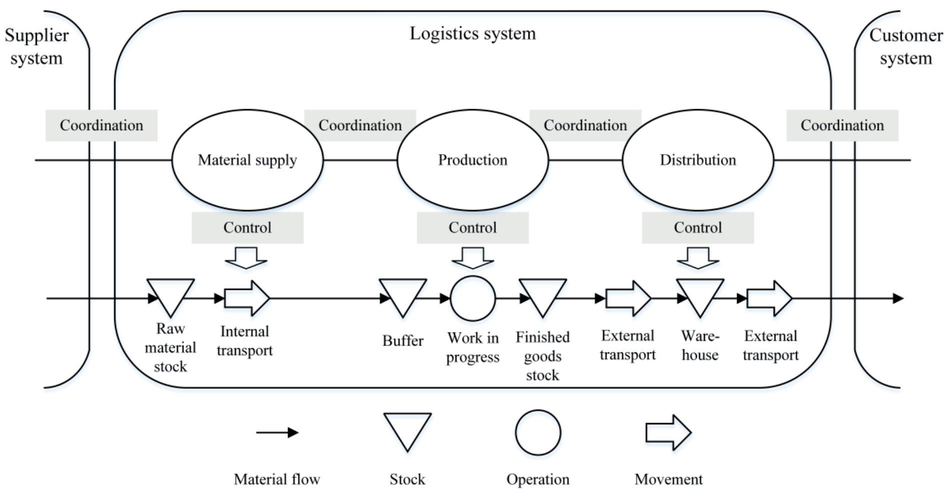

Figure 1: Logistics system with the company as a limit (Adapted from Jonsson (2008)).

Logistics can be divided into *structure* and *control* (Jonsson, 2008). Logistics structure concerns how the logistics system is set up with regard to its processes, the production layout, and the material flow structures, including material handling, transportation, and storage of goods. Logistics control concerns the implementation of efficient flows of material within the existing logistics structure (Jonsson, 2008).

Logistics is an applied science, offering solutions to actual, practical problems. Accordingly, logistics improvement requires a clear view of the context in which the logistics actions take place (Gudehus & Kotzab, 2012). In an internal logistics system, important factors that must be considered include the nature of the material in the system, key details of the jobs and work orders (e.g., due date, starting time), aspects of the system's physical environment, structural aspects of the system (e.g., the site layout, facilities, equipment used), and aspects related to the human operators in the system, including their roles and the number of operators (Mörth et al., 2020).

2.2 Engineer-to-order manufacturing

ETO is referred to as a product delivery strategy (Olhager, 2003), a customer order decoupling point (CODP) position (Wikner & Rudberg, 2005), a supply chain situation (Cannas & Gosling, 2021), or a production situation (Bertrand & Muntslag, 1993). The term is also used to classify companies utilizing ETO as their approach to manufacturing operations (Hicks et al., 2001) or the products produced by such companies (Willner et al., 2016). Typical ETO sectors include construction, machinery and capital goods, and shipbuilding, while certain new ETO sectors have emerged in literature in recent years, including mechanical engineering, consumer electronics, automotive, textile, railway, oil and gas, chemical, and aerospace (Cannas & Gosling, 2021). As is reflected by the list of sectors, ETO products are typically large, complex products that often include some sort of uniqueness in the designed and engineered solutions.

ETO is one of the four basic CODP positions, with the others being make-to-stock (MTS), assemble-to-order (ATO), and make-to-order (MTO). The CODP is the point in a product's value chain where the product is linked to a specific customer order (Olhager, 2010). Processes before this point are typically forecast driven, while after the CODP it is driven by actual customer orders. In ETO, the CODP is positioned at the design/engineering stage. This illustrates the key difference between ETO and the other CODP positions; all processes, even the design and engineering of the products, are to some degree customer order driven (Gosling

& Naim, 2009). This difference has implications for how production and supply chains are organized and managed.

Stavrulaki and Davis (2010) compares the four basic—and general—situations, according to characteristics related to the product, manufacturing, and logistics of each situation (see Table 1, which illustrates some of the aspects of ETO that have implications for operations and supply chain management).

Table 1: Comparison of the supply chain characteristics of the different CODPs (Adapted from Stavrulaki and Davis (2010)).

		MTS	**ATO**	**MTO**	**ETO**
Product characteristics	Demand uncertainty, profit margin, product variety, order lead time, labor skills.	Low			High
	Product life cycle, forecasting accuracy, volume	High			Low
Manufacturing related characteristics	Production process	Continuous, large volume assembly/batch	Assembly line processes	Small batch, job shops	Job shops, projects
	Product design	Cost conscious	Modular		Specialized
	Manufacturer has direct contact with end customer	Uncommon			Common
	Manufacturing process focus	Efficiency	Customer contact point defines decoupling point, efficiency/flexibility focus		Flexibility
Logistics related characteristics	Number of intermediaries between manufacturer and end customer	Large			Small
	Bullwhip effect	Prominent			Less likely
	Supplier relationships	Collaborative, high information sharing		Opportunistic collaboration, more collaborative barriers	
	Logistics process focus	Efficiency			Flexibility
	Supply chain strategic capability	Lean	Leagility		Agility

The most important characteristic of ETO manufacturing is the high customization of products that follows the placement of the CODP—products are designed and engineered after the receipt of a customer order, then manufactured, assembled, and delivered to the customer.

Accordingly, product variety is high, and flexibility is required in the manufacturing and logistics processes to accommodate customer requirements. Products with this kind of specialized design and engineering solutions tend to be large and complex. Consequently, order lead times in ETO are typically high, production requires high labor skills, and products are often managed as projects.

While “ETO” can denote a CODP position, there are different types of situations within that position. According to Bertrand and Muntslag (1993), ETO situations may differ in terms of the complexity of the products, the level of customization, the complexity of the layout and production process, and the market characteristics. Amaro et al. (1999) presents four types of ETO companies, which vary with respect to the processes the company is responsible for (design, specification, purchasing) and whether these processes are performed after receipt of a customer order. Hicks et al. (2001) describes four ideal ETO company types, differentiated by whether the design, engineering, manufacturing, and assembly processes are performed in-house. The four ideal types are the 1) vertically integrated company, the 2) design, engineering, and assembly company, the 3a) design, engineering, and contract company, and the 3b) project management company. These ideal types differ with respect to their main characteristics, such as core competencies, competitive advantage, vertical integration, supplier relationships, business environment, and type of risks. Willner et al. (2016) conceptualizes four archetypes of ETO products: complex, basic, repeatable, and non-competitive ETO. These are determined by two dimensions: annual units sold (average number of units sold over a period of n years) and engineering complexity (engineering hours per the average of annual units sold). Complex ETO products are produced in lower volumes and with a higher engineering complexity, for example, ships, oil platforms, and nuclear plants (Willner et al., 2016). Table 2 provides an overview of the main characteristics of complex ETO manufacturing.

Table 2: Main characteristics of complex ETO manufacturing (Strandhagen et al., 2019).

<u>Product characteristics:</u> • Large-sized, complex products with deep product structures (Sjøbakk et al., 2014; Zennaro et al., 2019) • High level of customization (Willner et al., 2016) • High product variety and low volume on the product level (one-of-a-kind products) (Adrodegari et al., 2015; Willner et al., 2016)
<u>Process characteristics:</u> • Manufacturing carried out as large projects in fixed position layouts (Willner et al., 2016) • Frequent changes (Sjøbakk et al., 2014) • Highly integrated and overlapping processes (Semini et al., 2014) • Focus on flexibility (Sjøbakk et al., 2014)
<u>Market characteristics:</u> • Customer order decoupling point located in the design stage (Gosling & Naim, 2009) • Fluctuations and uncertainty in mix and sales volume (Bertrand & Muntslag, 1993) • Uncertainty in product specifications (Bertrand & Muntslag, 1993)

ETO manufacturing may be classified as a type of manufacturing environment. The manufacturing environment (also referred to as “planning environment” and “production environment”) is the framework in which the manufacturing strategy is developed and implemented (APICS). It is the internal and external factors that affect the planning and control (Buer et al., 2018b). These factors describe the characteristics of the market, product, and manufacturing process, as shown in Table 2. The CODP placement influences a range of variables, including the level of customization, product variety, bill of materials (BOM) complexity, product data accuracy, P/D ratio (the ratio between the accumulated production lead time (P) and the delivery lead time (D) required by the customer), source of demand, volume/frequency, frequency of customer demand, time distributed demand, manufacturing mix, frequency of order repetition, fluctuations in capacity requirements, set-up times, and capacity flexibility (Buer et al., 2018b). Accordingly, in terms of manufacturing environments, an ETO situation has implications not only for production planning and control (PPC) in general but also for the internal logistics of ETO companies.

There are several aspects related to operations management that are affected by the characteristics of the ETO manufacturing environment. One of these is higher-level planning processes. In particular, there is often a lack of a structured process for overall PPC due to the complexity and variability of the products (Adrodegari et al., 2015). Generic frameworks for PPC, such as that of (Jacobs, 2011), do not fit the ETO manufacturing environment and require adaption. There are several reasons for this, emerging from the characteristics of ETO manufacturing described above. For example, as the CODP is located in the design stage in

ETO manufacturing, the customer is involved in both the design and engineering phases of the order delivery process. This results in several interactions between the manufacturer and customer, as they must agree on design specifications, technical solutions of the product, contract specifications, etc. The overall approach to PPC needs to reflect these interactions. Second, the high customization of each customer order—which is determined in the design and engineering phases and later realized in production—requires design and engineering work to be aligned with production. As this process structure is followed for each single order ETO manufacturing, the cross-functional aspects of ETO must be addressed in the overall planning approach. ETO manufacturers, as reflected in the ETO characteristics, typically produce large, complex products with deep product structures in low volumes and with long lead times. Accordingly, each order accounts for a large portion of the total work of an ETO manufacturer, as the work is split among a small number of end products. Thus, orders must be managed as projects, and project management, including project planning and control, must be part of the PPC approach. This contrasts with the PPC in more repetitive manufacturing environments. Finally, the complexity of the products produced in ETO manufacturing environments necessitates a comprehensive operational PPC system. Reflecting these aspects, frameworks for PPC for ETO differ from traditional PPC frameworks (Adrodegari et al., 2015).

With more specific attention to the operational aspects of ETO manufacturing, Bertrand and Muntslag (1993) describe the key characteristics affecting production control in ETO: dynamics, uncertainty, and complexity. ETO manufacturers experience strong fluctuations in product mix and sales volumes, even in the short and medium term (i.e., the market situation is dynamic). This contributes to uncertainty regarding the mix and volume of future demand, and demand forecasting is difficult considering the high customization of products. Furthermore, there is uncertainty related to product specifications (especially in early stages of design and engineering, when parts of the product are unknown) and process specifications (it is difficult to estimate the type and number of resources that will be required). Finally, there is considerable complexity in ETO manufacturing. This is due to the structure of the material flow, the internal structure of the manufacturing and assembly departments, and the management of several projects simultaneously. All these characteristics must be considered for effective production control in ETO situations (Bertrand & Muntslag, 1993).

As a specific example, complexity and dynamism are found to influence the applicability of lean practices (Birkie & Trucco, 2016). Some researchers have looked specifically at the application of value stream mapping (Braglia et al., 2006; Matt, 2014; Seth et al., 2017). There are several assumptions, or prerequisites, related to the application of several lean tools and methods, including value stream mapping (VSM). These prerequisites are straightforward and easily met in repetitive manufacturing environments, such as the make-to-stock environment, and even in make-to-order and assemble-to-order. In ETO, however, these prerequisites and assumptions do not fit to the same extent due to the specific circumstances of ETO manufacturing, such as the product, market, and process characteristics described above. Accordingly, the application of VSM and other tools and methods requires modifications or adjustments to fit in ETO. However, complexity and dynamism are also found to influence the operational performance benefits of lean practices (Birkie & Trucco, 2016). Complexity and dynamism are considered intrinsic factors in ETO. Hence, they make lean practices (if successfully implemented) more effective with regard to performance, as complexity and dynamism can be reduced or managed through lean practices.

Performance is another relevant aspect regarding ETO manufacturing—particularly, performance measurement. The applicability of performance measures depends on the context the measures are applied in (Gunasekaran & Kobu, 2007). For instance, certain generic performance measures for materials management are considered inapplicable in ETO, while some are considered only partly applicable (Sjøbakk et al., 2015). Accordingly, performance measurement system design for ETO must consider ETO characteristics to develop and combine measures that fit in such a manufacturing environment.

Other aspects of operations and supply chain management impacted by the ETO approach include engineering change management and the effect of engineering changes on production (Iakymenko et al., 2020), general principles for the design and operation of ETO supply chains (Gosling et al., 2015), supply chain coordination between actors in ETO (Mello et al., 2017), needs and requirements regarding software functionalities for PPC (Adrodegari et al., 2015), and the fit and applicability of planning methods (Jonsson & Mattsson, 2003). Finally, Zennaro et al. (2019) highlight the physical aspects of logistics related to managing both the many small parts as well as the big, heavy, customized and expensive components and sub-assemblies in the same logistics system, which is an issue in ETO manufacturing. They further emphasize the need for more research on material management in ETO.

2.2.1 Yard operations

A large and important type of operations within ETO manufacturing is yard operations. Yard operations is here used as an umbrella term for the physical and administrative tasks performed as a part of the production process at a yard. Yard operations are necessary to bring to life products such as cruise ships, offshore support vessels, oil platforms, modules, and other offshore structures. After-sales service operations are another segment within yard operations and ETO manufacturing (i.e., operations for providing service on existing products). Service jobs include maintenance, repair, conversion, upgrade, retrofit, and refurbishment. While this type of yard operation does not involve the production of new products, it is based on similar interactions with customers—a quotation and tendering process, including agreement on the work to be carried out, and the eventual contract signing—before customized production work begins on a ship or another type of product at the yard.

The businesses within yard operations can roughly be divided into shipbuilding (including after-sales service operations) and offshore construction, and these can be considered yard industries. These are both characterized by comprehensive and time-consuming development of large projects in close collaboration with the customer. Figure 2 illustrates the typical processes in such projects. They often involve a range of actors at different stages. The yard interacts with them in different ways, from receiving the design and engineering drawings from the designer to receiving materials from suppliers.

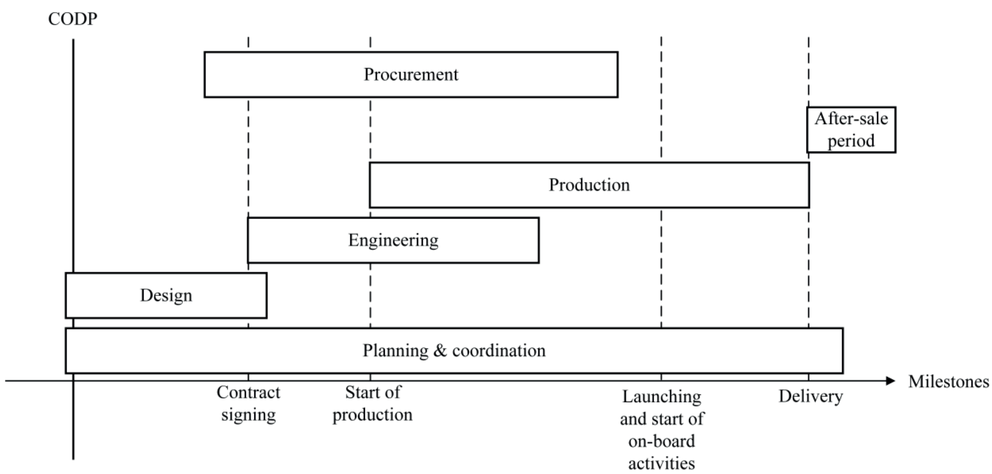

Figure 2: Processes in customized shipbuilding (Based on Semini et al. (2014)).

Figure 3 visualizes a shipbuilding supply chain and its main actors. The figure shows the large network of actors involved in such projects and the role of the yard in executing the production process—with information and material inputs from the other actors.

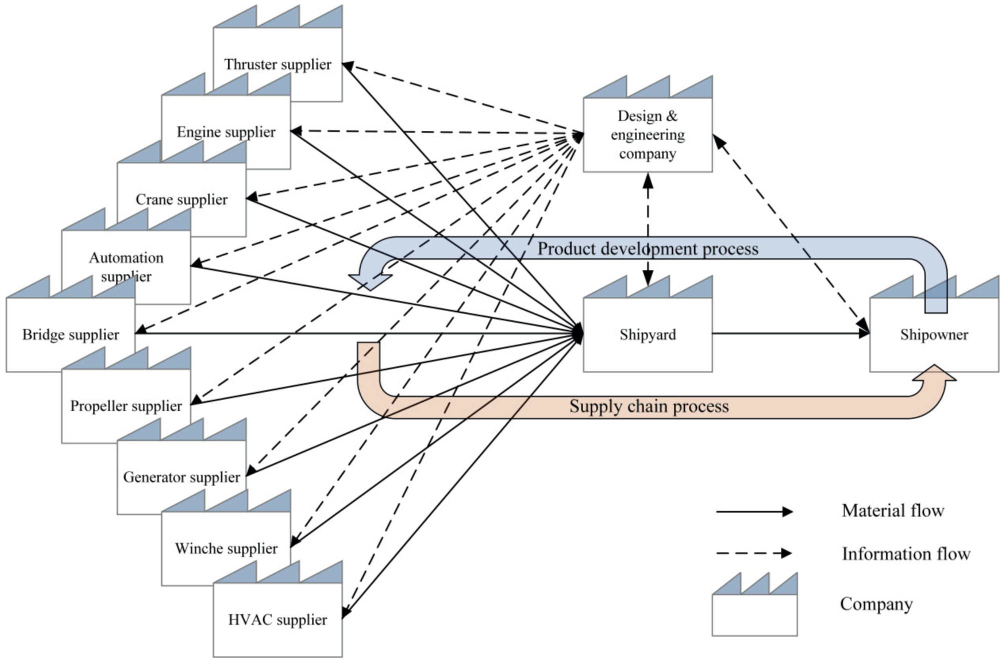

Figure 3: Actors in a shipbuilding supply chain (Adapted from Mello (2015)).

Another key characteristic of yard operations within this context is the engineering complexity related to the products (Willner et al., 2016) and, consequently, the complexity of the work to be carried out during the yard operations. Thus, yard operations rely on highly skilled workers within the various disciplines and comprehensive, detailed work instructions for the different jobs. Along with the high complexity of the products in yard operations, the size of the products and their numerous sub-assemblies, components, and parts must be considered. While yard operations are characterized by low-volume production on the end product level (i.e., production of a relatively small number of ships or offshore structures per year), the volumes on the component and part levels are high. Another consequence of these product characteristics is the need for heavy duty operations, including heavy lifts and internal transportation of large and heavy items. This requires specialized equipment and facilities—another distinguishing characteristic of this type of operation (Bruce, 2021)

Yard operations are to a large degree determined by the yard's production process. Table 3 provides a simplified and condensed overview of the stages of the production process. Some yards have limited their operations to a few stages of the complete production process, for example outfitting, commissioning, and testing (Semini, 2018). Accordingly, their general production process is different from that of so-called integrated shipyards, which perform all major stages of the production process themselves. In general, the production process in offshore construction is more or less similar to that in shipbuilding from a logistics perspective, although there are some variations between different types of offshore structures (El-Reedy, 2020). For instance, outfitting is not as relevant for the construction of jackets as they are for topsides. However, the production process at service yards differs greatly as such yards predominantly perform service jobs (e.g., repair, maintenance, conversion) on existing products and are not building new ones. The production processes of shipbuilding and offshore construction are covered in detail in existing literature (Bruce, 2021; El-Reedy, 2020; Hagen et al., 1996; Kanerva et al., 2002; Lamb, 2003).

Table 3: Simplified overview of the production stages involving yard operations (Based on Bruce (2021), El-Reedy (2020), Hagen et al. (1996), Kanerva et al. (2002), and Lamb (2003)).

Stages	**Descriptions**
Steel part production	Cutting and preparation of steel plates and profiles into individual parts for use in section and block building as well as prefabrication
Prefabrication	The production of components and parts for outfitting
Section and block building	The assembly of parts into sections and blocks by welding
Surface treatment	The surface preparation, priming, and painting of steel parts, sections, and blocks
Erection	The assembly of sections and blocks into the final product
Outfitting	The tasks related to the outfitting of a product, i.e., the installation of pipes and machinery; cabling and electrical systems; heating, ventilation, and air conditioning (HVAC); and accommodation and hotel functions (Semini et al. 2018)
Commissioning and testing	The startup and the testing of all systems and equipment against specifications
Service jobs	The tasks related to the execution of service at a yard during the operating phase of the product, such as maintenance, repair, conversion, upgrade, retrofit, and refurbishment

2.3 Digitalization

In 2011, a German government program published a report describing what was called the fourth industrial revolution: Industry 4.0. Mechanization, electrification, and automation characterized the three previous industrial revolutions, respectively (see Figure 4). The 2011 report pointed towards the next industrial revolution, enabled through the introduction of the Internet of Things and cyber-physical systems to form smart factories—grouped under the collective term digitalization. Following that report, and through rapid technological developments, digitalization has emerged as a major research category within operations management (Manikas et al., 2020).

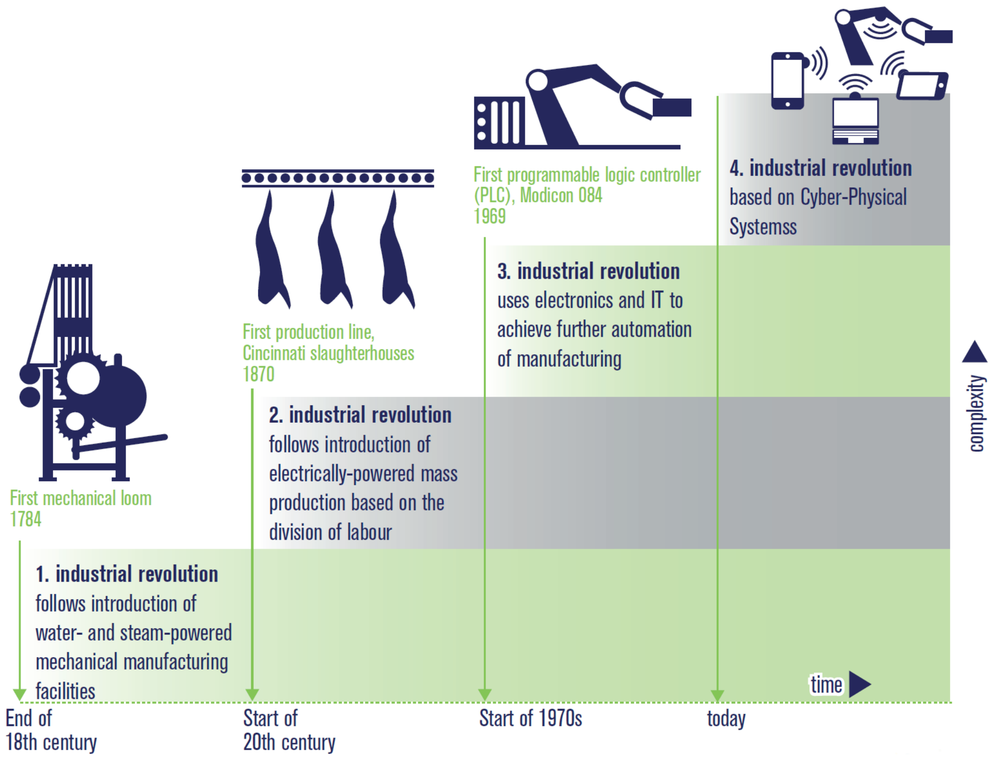

Figure 4: The four industrial revolutions (Kagermann et al., 2013).

The terms Industry 4.0 and digitalization are often used interchangeably. Digitalization may be considered the broader term, relating to most aspects of society and not only industry, while Industry 4.0 refers to the digitalization of industry, specifically.

For industry as a whole, Industry 4.0 promises disruptive changes that will impact organizational structures, business models, and business processes (Kagermann et al., 2013; Lasi et al., 2014; OECD, 2017). Most importantly—in the context of this study—digitalization will cause disruptive changes to industry (OECD, 2017).

There are different ways to conceptualize Industry 4.0. Frank et al. (2019) separates Industry 4.0 technologies into base technologies and front-end technologies (Figure 5). The Internet of Things (IoT), the cloud, Big Data, and analytics can be considered as base technologies, which provide the fundamental technological support necessary to achieve the end applications based on the front-end technologies. There are four dimensions of Industry 4.0 front-end technologies: smart supply chain, smart working, smart manufacturing, and smart product.

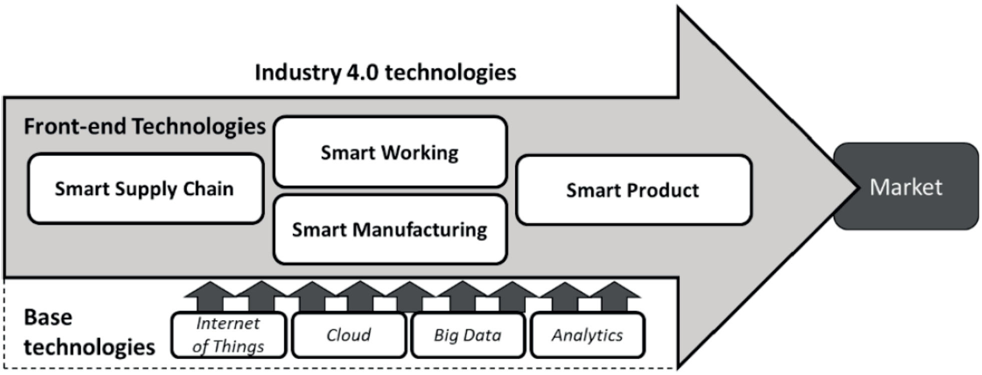

Figure 5: Conceptual framework for Industry 4.0 technologies (Frank et al., 2019).

In the literature, the base technologies are also referred to as enabling technologies or key components of Industry 4.0, although there are variations in which technologies are considered fundamental technologies for Industry 4.0. Fatorachian and Kazemi (2018) consider the IoT, the cloud, CPS, and Big Data analytics to be the four enabling technologies. Hofmann and Rüsch (2017) refer to CPS, the IoT, the Internet of Services (IoS), and smart factories as key components of Industry 4.0, where the smart factory component is enabled by the others. Another way to group the technologies associated with Industry 4.0 is as (a) technologies that generate data, (b) technologies that handle data, and (c) technologies that use data (Winkelhaus & Grosse, 2019).

Despite the variations in the conceptualizations and the lack of a clear definition of Industry 4.0 (Buer et al., 2018a), there is a broader acceptance of the big picture of Industry 4.0, including its benefits, key technologies, requirements, and barriers (Da Silva et al., 2020). Research in the field is now increasingly aimed at investigating the practical applications of Industry 4.0 technologies (Zheng et al., 2021). More detailed explanations and descriptions of Industry 4.0 and its constituents in general are provided in papers 4, 5, and 6.

Digitalization will indeed impact the range of supply chain stages, such as product development, procurement, production, logistics, inventory management, and retailing (Fatorachian & Kazemi, 2020). Production and logistics are at the center of attention for developments related to Industry 4.0 and digitalization, and there are many expected benefits, including improved product customization, improved product quality, reduced operational costs, increased productivity, reduced product launch time, improved sustainability, increased process visualization and control, and improved worker satisfaction (Dalenogare et al., 2018). Specifically for logistics, some of the key advancements include real-time capabilities, dynamic planning and control, autonomy, visibility and traceability, material identification and tracking, automation of internal transportation and material handling, as well as operator assistance in various logistics activities (Bueno et al., 2020; Zheng et al., 2021). Moreover, in their literature review, Winkelhaus and Grosse (2019) found that Industry 4.0 technology had a great influence on the intralogistics domain of logistics.

There have been numerous efforts to group or categorize the different technologies associated with Industry 4.0 in manufacturing. Table 4 provides an overview of one possible way of listing the technologies with descriptions, and further details regarding digital technologies and their applications can be found in papers 4, 5, and 6.

Table 4: Overview and description of digital technologies in manufacturing logistics (Strandhagen et al., 2019).

Technology group	Description
Additive manufacturing	3D printing of objects layer by layer, based on 3D models or CAD files of the objects.
Autonomous robots	Automatic guided vehicles (AGVs), autonomous mobile robots (AMRs), and collaborative robots (COBOTS) for material handling and performing logistics operations.
Cloud manufacturing	Cloud-based solutions for sharing and exchange of data between systems, sites, and companies.
Cyber security	The secure and reliable protection of industrial production systems from cyber threats.
Data analytics	Transforming data into knowledge and actions within a manufacturing system. Big Data for analysis of large sets of real-time data, artificial intelligence, machine learning, and advanced simulations are all part of this group.
Integration of IT systems	Horizontal and vertical integration of IT systems for production management (PLM, ERP, MES).
Internet of Things	Objects equipped with sensors and actuators, enabling storing and exchange of information through network technology.
Visual technology	The visual representation of an object, in the form of augmented reality (AR), through superimposing a computer-generated 3D image in the real world, creating a virtual reality (VR), or projecting 3D images as holograms.

The development and availability of technology, however, is not sufficient for the manufacturing industry to reach the vision of Industry 4.0. An equally important aspect is the operationalization, and eventually the implementation, of the available technologies (Fatorachian & Kazemi, 2018). As companies and organizations move further along the processes of Industry 4.0 technology implementation, it will become possible to say more about best practices. Some research efforts have already been carried out in this regard (Frank et al., 2019), although it still seems early—and further research, pilot projects, and practical implementations are necessary.

Furthermore, there are several potential barriers to the implementation of digital technologies, including governmental, financial, technological, organizational, and human resource-related aspects (Da Silva et al., 2020; Glass et al., 2018; Raj et al., 2019). Table 5 lists a set of the barriers that have been identified in recent literature and empirical studies.

Table 5: Barriers to the implementation of Industry 4.0 technologies in manufacturing (Da Silva et al., 2020; Glass et al., 2018; Raj et al., 2019).

Barriers	**Description**
High investment costs.	Implementation of digital technologies may require significant capital investments, which may pose a challenge for companies.
Lack of clarity or understanding of the economic benefits.	Without a clear understanding and proof of the economic benefits of technology applications, companies may be reluctant to invest in implementation.
Challenges in or lack of supply chain integration and collaboration.	The realization of certain potential benefits of Industry 4.0 technologies requires close collaboration and tighter integration across supply chain actors, which may be both challenging and undesirable.
Low maturity level of technologies.	While the technological developments may have come far, their industrial application may still be at a low level of maturity, or technology readiness level (TRL). This may cause reluctance to implement them.
Lack of standards, governmental regulations, and policies.	The implementation of rapidly developing advanced technologies may be hindered by a lack of associated standards, regulations, and policies, which are developing at a slower pace.
Inadequate technological infrastructure.	The advanced technologies of Industry 4.0 require a certain level of technological infrastructure to be applicable in the industrial context. Accordingly, inadequate technological infrastructure may prevent technology implementation.
Lack of human resources and digital skills.	A lack of knowledge and skills among employees regarding the use of digital technologies, and a lack of human resources dedicated to digitalization-related activities, may impede companies' ability to use the desired technologies.
Internal resistance to change.	Resistance or unwillingness of employees to change their way of working or working methods may be a barrier to implementation, as new digital technologies may disrupt or require changes in traditional practices.
Ineffective change management.	The transition to Industry 4.0 technology application may be complex and challenging and may require highly effective change management.
Lack of, or difficulties in forming, a digitalization strategy.	A comprehensive implementation of and transition to Industry 4.0 technologies can require significant changes to a company's operations. Accordingly, a strategy for digitalization may be necessary.

Another important aspect with regards to Industry 4.0 technology application is context dependence. This is relevant in several areas of operations management, such as quality management (Sousa & Voss, 2001), lean manufacturing practices (Buer et al., 2021), the use of manufacturing planning and control methods (Jonsson & Mattsson, 2003), manufacturing technologies (Congden, 2005), and production control systems (Fernandes & Godinho Filho, 2011). Although there is still a lack of research on the context dependence of the fit and applicability of Industry 4.0 technologies, a reasonable assumption would be that the minority of Industry 4.0 technologies are universally applicable. There is some existing research on how contextual factors such as company size and manufacturing environment impact the digitalization of production. While company size seems to have an impact on the implementation of digital technologies, it is still uncertain whether the type of manufacturing environment has an impact (Buer et al., 2020). However, there are indications that certain technologies are more or less applicable and more or less beneficial in different manufacturing environments. Another take is that technologies must be applied *differently* depending on the context.

2.4 Logistics and digitalization in yard operations

As mentioned in section 1.2, there is a lack of holistic and structured knowledge on yard logistics. Existing works related to yard logistics are typically found within the literature streams for shipbuilding and offshore construction. The shipbuilding literature has its background in naval architecture, while literature on offshore construction is typically found within the field of offshore engineering. Accordingly, the logistics perspective is not common within shipbuilding and offshore construction, and there is a lack of research on the more specific topic of yard logistics. While there is some, it is still limited, scattered, and unstructured. However, there are several works that are related to yard logistics, and to some extent covers parts of it.

Storch et al. (1995) and Eyres and Bruce (2012) are two of the most relevant textbooks with regards to the topics of this study. They cover a wide range of aspects of shipbuilding. However, these works are primarily focused on the production process and some after sales services, and to some extent the business of shipbuilding. Accordingly, there is limited focus on aspects related to internal logistics at yards. They do cover shipyard layouts to some extent, although with a production perspective rather than a logistics perspective. Moreover, the coverage is primarily relevant for large-scale shipyards. Comparably, El-Reedy (2020) covers offshore structures and platforms, however, with a focus on the design and engineering aspects.

More recently, there has been efforts to develop and structure knowledge that incorporate the management aspects of shipbuilding—in general (Bruce, 2021) and more specifically regarding production management (Woo & Song, 2014). The need to integrate these aspects with the production and engineering dominated aspects in shipbuilding research is gaining recognition—although the literature is still dominated by a focus on large-scale shipyards. Bruce (2021) cover several aspects of shipbuilding management that are relevant for yard logistics, such as materials management and the physical flows of material through the main stages of the production process. Furthermore, the textbook includes reflections on typical shipyard layouts, as shown in Figure 6, as well as on how the placement of facilities, areas, and equipment in relation to each other determine certain aspects of the material flow. Such reflections, although based on the author's personal views and experience (Bruce, 2021), are useful in the exploration of the more specific topic of yard logistics in the present study.

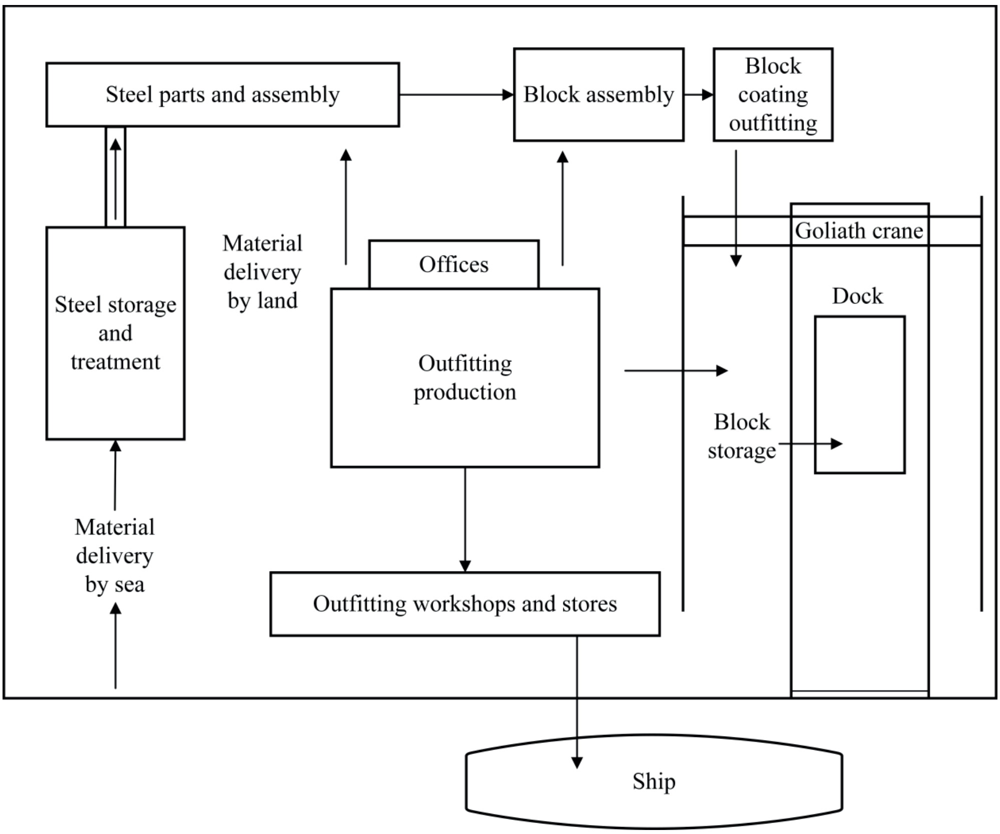

Figure 6: Typical shipyard layout (Adapted from Bruce (2021)).

In addition to Woo and Song (2014), which systematize production management in shipbuilding, there are a few academic articles addressing topics that can be placed within, or at least in relation to the definition of yard logistics of this study. The most dominant topics of existing, related research are shipbuilding production planning and scheduling (Ju et al., 2020; Lee et al., 2018; Lee et al., 2020; Nam et al., 2018; Rose et al., 2016), layout planning and optimization (Choi et al., 2017; Dixit et al., 2020; Liu et al., 2013), spatial arrangement planning and optimization (Dai et al., 2015; Jeong et al., 2018a; Zheng et al., 2012; Zhuo et al., 2012) the flow of ship blocks (Jeong et al., 2018b; Joo & Kim, 2014), and production control (Park et al., 2020; Yue et al., 2018). Common for most of these is the use of simulation of mathematical approaches to solve planning or logistics-related problems, typically at large-scale shipyards. Some have addressed more specific areas within yard operations, such as ship outfitting (Wei, 2012), ship maintenance (Sinha et al., 2005), and offshore construction (Gi Back et al., 2017), but there is an evident scarcity of such works and their logistics focus is limited.

Research have highlighted a lack of advancements of digitalization in ETO in general (Zennaro et al., 2019). From the literature reviews, this lack seems to apply also to yard logistics specifically. There are a few articles addressing various aspects of digitalization of shipbuilding in general (reviewed in papers 5 and 6). They are predominantly exploring the broad outlines of digitalization of the shipbuilding industry (Beifert et al., 2018; Blanco-Novoa et al., 2018; Fernández-Caramés et al., 2018; Jha, 2016; Joe & Chang, 2017; Munín-Doce et al., 2020; Para-González & Mascaraque-Ramírez, 2020; Ramirez-Peña et al., 2019; Ramirez-Peña et al., 2020; Sanchez-Gonzalez et al., 2019; Stanić et al., 2018), with only a few investigating the application of digital technologies at yards.

2.5 Key constructs and research framework

In theory building research, it is necessary to have an initial view of the general constructs or categories to be studied, and their relationships (Voss et al., 2016). As a part of the research process, a research framework needs to be developed—a conceptual model of what is to be studied (Karlsson, 2016). Such a framework guides the research process, and enables data collection and data analysis of the intended areas or aspects (Åhlström, 2016). The research framework of this thesis is built around the constructs described in Table 6.

Table 6: Overview of the main constructs in the study.

Construct	Definition
Yard	An industrial site for production and servicing of ships and/or offshore maritime installations.
Yard environment	The internal and external factors that affect yard logistics.
Yard operations	All physical and administrative tasks performed as a part of the production process at a yard.
Yard logistics	The coordination of the yard operations concerned with the flow of materials and information through the yard up to the production of the end product.
Yard logistics performance	The performance of the yard logistics system with regard to productivity, value-adding time, and throughput time.
Digitalization	The use of digital technologies (Industry 4.0 technologies) to digitalize operations.

The intention of the research framework is to graphically visualize the main areas to be studied and the relationships among them. Additionally, it serves as a guide in the research process.

Recalling that the main objective of the study is *to develop knowledge on yard logistics needed to improve yard logistics performance and identify how digitalization can support this improvement*, the research framework shown in Figure 7 was developed.

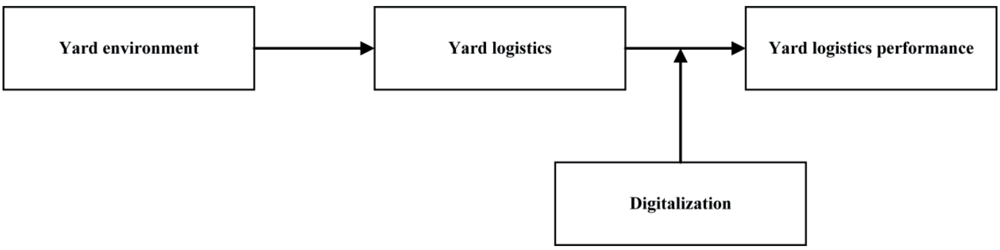

Figure 7: Research framework.

Yard logistics performance is the dependent variable in the framework and is affected by yard logistics. Yard logistics is further dependent on the yard environment. It is assumed that digitalization moderates the relationship between yard logistics and yard logistics performance. These constructs and the relationships among them are explored in the appended papers as well as in this main report.

3 Research design

This chapter describes the research design of this study. It builds on the research objective and research questions presented in Chapter 1 and presents the overall research approach as well as the selected research methods. The chapter reflects on the main decisions made in the research design process and addresses how research quality has been ensured.

3.1 Research methodology

An essential part of this PhD study concerns understanding, exploring, and explaining a particular context, as it seeks to investigate yard logistics. This feature of the study aligns well with a qualitative approach, which is particularly useful when seeking to understand real-world situations and their patterns and structural features (Flick et al., 2004). Accordingly, the project targets qualitative data, which can be powerful for both discovering and exploring new ideas (Miles et al., 2014)—consistent with the research objective and questions.

A key consideration in choosing a research approach is the methodological fit between the research questions, the maturity of knowledge available on the research topic, the research approach, and the ultimate contribution of the research (Åhlström, 2016). As indicated by the research objective and questions presented in Chapter 1, this study seeks to explore, understand, and explain the particular context of yard logistics—in general and with regards to digitalization. Thus, case research was considered to be an appropriate method, and the PhD study is comprised of five separate case studies (see Table 7), involving in total 14 cases (see Table 9).

Extensive literature reviews, although not explicitly stated as a research method in this study, provide a foundation for the research conducted in this study. Further elaborations on how the literature has been used are provided in the appended papers.

Table 7: Overview of the case studies in the PhD study.

#	Case study design type	Cases	Unit of analysis	Reported in paper #
I	Multiple-case study	D, F, I, K	Factory	4
II	Single-case study	M	Yard	6
III	Single-case study	M	Supply chain	5
IV	Multiple-case study	H, L, M	Yard	3
V	Multiple-case study	A, B, C, E, G, J, M, N	Yard	1, 2

Table 8 provides an overview of the research design, linking research questions to the case studies, their outcomes, and in which sections and papers the research has been reported. The overview, as well as the overall structure of the thesis, is in a thematic order from the fundamentals of yard logistics to the ultimate digitalization of yard logistics. However, that thematic order emerged from a research process that originated from a need to understand the contextual implications on the applicability of digital technologies in manufacturing logistics. Investigations on this applicability in different manufacturing environments (case study I) revealed how the special circumstances of ETO may require further exploration with regards to digitalization. This was the starting point for initial visits to and investigations of case yard M, with the aim of exploring how yard logistics—as a type of ETO logistics system—can be digitalized (case study II) and the potential impact digitalization can have across entire supply chains in yard industries (case study III). Our investigations of case yard M revealed the need for enhanced, general understanding of yard logistics to be able to prescribe digitalization of yard logistics. Therefore, we initiated a study to investigate the factors affecting yard logistics, and their implications—while also comparing a Norwegian shipyard to two South Korean shipyards (case study IV). This research on yard logistics identified the need for an even more fundamental exploration—and knowledge development—of the field of yard logistics, resulting in case study V, the most comprehensive of them all, comprising 8 yards. This case study provided the empirical data necessary to define and characterize yard logistics, identify its constituents, develop performance measures, and assess challenges. This knowledge was deemed essential to fully comprehend yard logistics, develop efficient logistics solutions, and the digital solutions that can advance yard logistics. Building upon the knowledge developed in these case studies, this PhD study was completed with the development of a concept for digitalized yard logistics, providing a conceptual basis to support further digitalization efforts.

Table 8: Overview of the research design, linking the research questions, case studies, outcomes, and sections and papers.

Research questions (RQs)	**Case studies**	**Outcomes**	**Reported in**
RQ1: How can yard logistics be conceptualized?	Case study V	Definition and characterization of yard logistics, including the constituents of yard logistics, according to a typology of yard operations	Sub-sections 4.1.1, 4.1.2, 4.1.3, and 4.1.4 paper 1
		Identification of yard logistics challenges	Sub-section 4.1.5; paper 1
		Performance measurement system for yard logistics	Sub-section 4.1.6; paper 2
	Case study IV	Identification of factors affecting yard logistics	Sub-section 4.1.7; paper 3
RQ2: How can digital technologies be applied to contribute to more efficient yard logistics?	Case study I	Insights into the context-dependency of the applicability of Industry 4.0 technologies	Sub-section 4.2.1; paper 4
	Case study III	An outline of the potential impact of digitalization across entire supply chains in yard industries	Sub-section 4.2.2, paper 5
	Case study II	Identification of the required features of a digitalized yard logistics system	Sub-section 4.2.3, paper 6
	Case study V	Overview of the current state of digitalization in yard logistics	Sub-section 4.2.4
		Concept for digitalized yard logistics	Sub-section 4.2.5

3.2 Case research

Case research focuses on understanding the dynamics present within single settings (Eisenhardt, 1989). It allows a phenomenon to be studied in its natural setting and provides understanding through observing actual practice (Meredith, 1998). Case research is the method that is based on the use of case studies and is one of the most powerful methods in operations management (Voss et al., 2016). Yin (2018) describes case study research as a linear but iterative process, which includes the following steps: plan, design, prepare, collect, analyze, and share. The steps and how they are handled in this study are presented in the following paragraphs.

Plan

A key first step is the decision and justification of selecting case research as an appropriate method for the research problem to be investigated. Case research is particularly strong for theory building—identifying and describing key constructs, patterns, or linkages between variables—with an inductive research approach (Voss et al., 2016). Inductive research contributes to theory through the development of explanations based on empirical observations. Case research allows research questions of *why, what*, and *how* to be answered with a relatively full understanding of the complete phenomenon (Meredith, 1998). The case research approach is common within operations management, and this approach is particularly relevant when the context is important (Voss et al., 2016). Furthermore, within the topics addressed in this PhD study, there is a need for more empirical studies and qualitative case research to enable further knowledge development. Therefore, case research has been selected as the main research method for this study, as it will make it possible to understand the yard logistics context, which is key in this research, and it is considered the most appropriate method to answer both RQ1 and RQ2.

Design

The case study research design step includes the selection and definition of the unit of analysis (Voss et al., 2016; Yin, 2018). Typical units of analysis in case research within operations management are companies, sites, supply chains, products, or projects. Clearly stating and defining the unit of analysis clarifies what is being studied. In this study, the main unit of analysis is yards, which makes it possible to answer the research questions accurately. However, as the overall study consists of several case studies, some of the studies were designed with different units of analysis (case studies I and III). For the PhD study in general, the unit of analysis is yards—in the context of ETO manufacturing, as described in section 1.4.

The design phase also involves the selection of the case study design type. There are four main types of designs: single-case and multiple-case designs, and within each of the two, single or multiple units of analysis (so-called embedded units of analysis) (Yin, 2018). The design also includes the choice of whether to use retrospective or current cases (Voss et al., 2016). Each case study design type has advantages and disadvantages, and the appropriateness of the different design types depends on the nature of the research problem and the specific research questions to be answered. This study includes both single-case and multiple-case studies, all using current cases and single units of analysis within each case (see Table 7). The respective papers provide justifications of the case study designs used.

Prepare

The case study design step is followed by data collection preparation. This step should include development of a case study protocol, screening candidate cases, and conducting a pilot case study (Yin, 2018). A case study protocol is essential when performing multiple-case studies and contains the procedures and general rules to be followed before, during, and after the case study (Yin, 2018). A case study protocol was particularly important for case study V (Appendix A) as it was the most comprehensive case study. It included an overview of the case study, the data collection procedures, and the questions to answer—ensuring that for each case, the data collection was targeted on the topic of the study, and that the same procedures were followed for each case.

The case selection was a separate process for each of the case studies and is described in the respective papers. In general, however, the cases have primarily been selected from within Norwegian industry. This is due to convenience and accessibility with regards to data collection, as well as to ensure the relevance with regards to the industrial challenges outlined in Chapter 1. As described in section 3.1, case study I was conducted before the scope of the thesis was targeted on yards and yard logistics. The factories in case study I were selected to represent a wide range of manufacturing environments—from MTS to ETO—with the purpose of investigating how the manufacturing environment affects the applicability of digital technologies in manufacturing logistics. For the single-case studies (II and III in Table 7), with the scope targeted on the yard context, one candidate stood out as highly accessible and the one of which the involved researchers had the most existing information and knowledge available. As the candidate was also found to be suitable for answering the research questions related to the case studies, the choice was simple. The exception from the selection of Norwegian cases is case study IV, which included two South Korean shipyards, with the purpose of highlighting logistics differences due to contextual differences. Case study V involved the most comprehensive and careful screening and case selection process, as it had the highest number of cases. Furthermore, the case study was piloted to test and refine the data collection plans and procedures. This case study was again targeted towards the Norwegian context, and only Norwegian yards were selected. Further details on case study 5 are provided in papers 1 and 2

Table 9 gives an overview of the cases used in the case studies, specifying their primary focus.

Table 9: Overview of cases included in the case studies.

Case	Primary focus
A	Production of (complete) oil platforms and modules, and offshore wind platforms
B	Production of floating offshore platforms, platform topsides, onshore facilities for oil and gas processing, offshore wind platforms
C	Production of steel jackets for offshore platforms, offshore wind jackets, subsea structures
D	Development and production of thruster systems for maneuvering and propulsion of advanced ships
E	Smaller service operations on a range of different types of ships
F	Production of recliner chairs, sofas, and other home furniture products
G	Refurbishments, rebuilds, repairs, upgrades, and smaller service operations on different types of ships, and some outfitting operation
H	Integrated shipbuilding of customized vessels for offshore and maritime transport markets
I	Outfitting operations on advanced and customized ships
J	Outfitting and service operations on ships for offshore, fishery and other types of specialized vessels
K	Production of plastic pipes for various purposes, including water supply and sewage, heating ventilation and sanitation, cable protection, wiring and gas pipes
L	Integrated shipbuilding of customized vessels for the maritime transport market
M	Outfitting and commissioning of advanced and customized ships
N	Outfitting operations on advanced and customized ships

Collect

The data collection for all case studies that are part of this research followed Yin's generic principles of data collection in case research (Yin, 2018):

- Use multiple sources of evidence, allowing data triangulation, as the multiple sources of evidence provide multiple measures of the same phenomenon. Accordingly, the evidence may be converged to corroborate the same finding, thus adding strength and construct validity to the case study.
- Create a case study database for organizing and documenting the collected data. The case study database is a tool that allows the collected data to be stored in a structured way and kept easily available. Accordingly, it provides support for subsequent analysis of the data.
- Maintain a chain of evidence, meaning that there is a chained link between the research questions, through the case study protocol, citations to evidence, the case study database, and the case study findings.

A key issue in case research is what data to collect. There are six primary sources of evidence that can be targeted in case research: documentation, archival records, interviews, direct observations, participant observation, and physical artifacts. Participant observation and physical artifacts were considered non-relevant sources in this particular study, whereas the other four as highly relevant. Detailed descriptions of the data collected for each case study are provided in the respective papers. However, the list below provides a general overview of the main case data sources used in the case studies:

- Interviews (semi-structured) with key personnel at the selected yards on specific topics
- Direct observations at the selected yards through site tours
- Archival records, such as product catalogs, organizational charts, and process and layout.
- Existing documentation, such as background information on the industry and news articles

With the overall qualitative approach of the research, the data collection was aimed at gathering mainly qualitative data through these types of data sources. They all have certain strengths and weaknesses (Yin, 2018), and by using multiple sources the weaknesses of the single sources can be compensated for. As an example, an interviewee's description of yard logistics activities could be compared against our (the involved researchers) own direct observations at the yards.

For the purpose of investigating manufacturing logistics systems, the data collection process was based on the control model methodology (Alfnes, 2005; Alfnes & Strandhagen, 2000). This methodology was developed for mapping and analyzing manufacturing logistics aspects. It is particularly useful for providing a holistic understanding of a manufacturing logistics system, and its general framework was used to guide the data collection.

Analyze

The data analysis, in general, contained three concurrent flows of activity: data condensation, data display, and extracting and verifying the findings (Miles et al., 2014). Data were condensed by selecting, focusing, simplifying, abstracting, and transforming the data from the evidence sources used: field notes from yard tours, interview transcripts, existing documentation, etc. The data condensation activity followed the general analytic strategy of developing case descriptions from the collected data and organizing them according to descriptive frameworks matching the main topics the data were collected on (Yin, 2018). This strategy made it possible to organize and extract information on the predefined topics of interest. As an example, for the data analysis for case study 5, case descriptions for each case were developed and organized according to a set of yard logistics constituents. For each case, each yard logistics constituent was described by the collected data, allowing further analysis based on that descriptive framework.

Data condensation is a process that makes the (raw) data stronger and prepares the data for the next activity, data display, which involves constructing displays that present data in the form of extended text, tables, matrices, lists, visualizations, etc. These kinds of data displays have been used extensively throughout this study—both as pure, back-end analytical tools and to produce the front-end data displays presenting the results and findings in the appended papers. For both purposes, the data displays augment the understanding of the data and allow analytic reflection.

The third main activity of the data analysis is to extract and verify findings from the data. This activity occurs in parallel with the data collection—from its start—and involves a continuous interpretation of the data by noting patterns, explanations, and causal relationships. Then, as the data analysis proceeds, the findings are further verified in the interplay between the data condensation and data display processes.

As an extension of the analysis step, the case research has included a concept development activity related to the concept for digitalized yard logistics. This concept development activity is inspired by the design science research (DSR) method, which aims at developing generic knowledge from real field problems, with generic designs as the core research product (van Aken et al., 2016). The research product of DSR can eventually take the form of a construct, a model, a method, or an instantiation (Hevner et al., 2004). In this PhD study, the concept development activity utilized the previously described case studies, which explicate the challenges of yard logistics and identify the requirements for digitalized yard logistics. Accordingly, the case studies were the contextual or environmental foundation for the concept development, providing an understanding of the particular field problems of yard logistics. Similar as a design science activity, the concept development activity was connected to the scientific knowledge base through being built on reviews of applicable digital technologies. These informed and guided the concept development. Accordingly, with an understanding of the yard logistics context through case studies, and a connection to the state of the art of digitalization, a concept for digitalized yard logistics could be developed. It is presented in sub-section 4.2.5.

Share

The final step in the case study research process is to share the research, which has been done in the appended papers—academic research papers. The main issue in this step concerns the case identities. Disclosing the case identities is the preferred option, as it allows the reader to recollect any other information on the same case, while anonymity may be necessary or wanted on certain occasions (Yin, 2018). In this study, this was a separate choice for each of the five case studies. For case studies I-IV anonymity was deemed unnecessary, and the case identities were disclosed in the respective papers. For case study V it was decided together with the cases to anonymize the case identities as a precaution to avoid any unwanted distribution of critical information that may be exploited by anyone.

3.3 Ensuring research quality

Research quality is essentially about ensuring trustworthiness—that is, that the research applies appropriate methods, data collection procedures, and analyses and that conclusions are thoughtful and reasonable with respect to what is being studied (Karlsson, 2016). Certain key elements of research quality have already been covered in sections 3.1 and 3.2, such as the explanation and justification of the research approach, including the case selection process and decisions, and the clarification of the unit of analysis. Research questions should be clearly stated, and the research should be grounded in existing theory, clarifying the role of theory in the research. In operations management research, there are four particularly relevant requirements for research quality: construct validity, internal validity, external validity, and reliability (Karlsson, 2016). Indeed, these may be used as tests for judging research quality (Yin, 2018). For each requirement there are certain tactics that can be applied throughout the research process to ensure trustworthiness and thus research quality. The previous section has described some of the tactics that have been applied in this study. This section will address these more explicitly in relation to each of the four requirements for research quality.

3.3.1 Construct validity

Construct validity is about using the correct operational measures (Yin, 2018). This means that the operational measures the study uses to measure different constructs actually measure what they are intended to measure (Karlsson, 2016). It must be ensured that the study investigates what it claims to investigate (Voss et al., 2016).

Properly defined constructs are crucial for ensuring construct validity, and those constructs must be linked to research objectives and questions and supported by identified operational measures that match the constructs (Yin, 2018).

Using multiple sources of evidence and maintaining a chain of evidence from research questions to findings are two case study tactics that have been applied to contribute to the construct validity in this study. Explicit statements and explanations of the data collection procedures can be found in the appended papers. Further, explanations of the data analysis procedure—how the data were analyzed—further strengthens the construct validity of this study.

3.3.2 Internal validity

According to Karlsson (2016), "Internal validity means that the study actually measures what is meant to measure and that demonstrated relationships are explained by the factors described and not by other factors" (p. 31).

Internal validity is mainly a concern in explanatory case studies, that is, studies concluding that there is a causal relationship between X and Y. If such a study fails to recognize that a third factor Z may have caused Y, then there is an internal validity issue.

Due to the exploratory and descriptive features of the case studies in this PhD study, internal validity has not been as critical. However, relevant causal relationships have been investigated with theoretical demonstrations of the logical causal relationships in the development of the conceptual research framework and through explanation building in the data analysis phases of the different case studies. It has been suggested that these two case study tactics can ensure internal validity in case research (Voss et al., 2016).

3.3.3 External validity

"External validity means that the results are valid in similar settings outside the studied objects" (Karlsson, 2016, p. 31). External validity relates to the generalizability of a study's findings—a common concern in case study research (Yin, 2018). This refers to whether the findings can be generalized beyond the immediate case study (Voss et al., 2016). Yin (2018) urges to view case studies as opportunities to shed empirical light on some theoretical aspects, and not viewing the case(s) as a sample. In case studies, generalizations are made from one case to the next, framed by existing theory, and not to a larger universe (Miles et al., 2014). This is called analytical generalizations—expanding and generalizing theories—in contrast to statistical generalizations (Yin, 2018).

Specifically, for the multiple-case studies in this PhD study, external validity was sought by using a replication logic in the case selection, as is suggested for multiple-case studies (Voss et al., 2016). Replication logic—as opposed to sampling logic, in which the cases could be viewed similarly to multiple respondents in a survey—aims to identify both similar and contrasting results from each of the selected cases in a study (Yin, 2018). Based on this logic, cases are carefully selected to predict similar results (literal replications) or contrasting results but for predictable reasons (theoretical replications).

3.3.4 Reliability

According to Karlsson (2016), "reliability means that the study is objective in the sense that other researchers should reach the same conclusions in the same setting" (p. 31). Although opportunities for repeating case studies are rare, their reliability still relies on strong documentation regarding how the studies were conducted.

A transparent research process, including proper documentation of all necessary information, is one of the factors that enables reliability (Voss et al., 2016). Transparency in research allows replication by others. In all the appended papers, the research processes of the respective studies are explained explicitly, describing the steps followed in the research.

Case study protocols and case study databases are key instruments that have been used to ensure reliability in this PhD study. They provided structure and allowed proper documentation during the data collection phase. Both instruments are described in more detail in section 3.2 as well as in the relevant papers.

4 Results

This chapter presents the main research results of the study. It establishes the link between them, providing answers to the study's research questions. The chapter is structured in two sections, each presenting results related to one of the two research questions of the study.

Based on the five case studies that were carried out as a part of this research, results were developed that, together, provide answers to the research questions. To answer research question 1—conceptualizing yard logistics—this research defines and describes yard logistics, its main activities, as well as its main constituents and key characteristics according to a typology of yard operations. The research further identifies and describes yard logistics challenges, contextualized performance measurement to yard logistics, and identified the factors affecting yard logistics. Together, these results, presented in section 4.1, enable a holistic understanding, and provide a structured overview of yard logistics. This fundamental knowledge is considered necessary to be able to develop efficient logistics solutions that increase cost-efficiency, and to develop efficient solutions for digitalized yard logistics.

To answer research question 2—investigations on the digitalization of yard logistics—this research provides insights on the context-dependency of Industry 4.0 technologies and outlines the potential impact of digitalization across entire supply chains in yard industries. Further it identifies the required features of a digitalized yard logistics system and provides an overview of the current state of digitalization in yard logistics. Finally, the research includes the development of a proposed concept for digitalized yard logistics. These results, presented in section 4.2, show how digital technologies can be applied to contribute to more efficient yard logistics.

4.1 Yard logistics

This section presents the results and findings related to the first research question: *How can yard logistics be conceptualized?* The section is based on the research presented in papers 1, 2, and 3.

4.1.1 Defining yard logistics

Yards in this context are industrial sites for production and servicing of ships (shipyards) and offshore maritime installations (offshore construction yards). They are facilities used for the production and service of large, complex, and customized products and can be characterized as follows:

- Large areas at an outdoor site, with several facilities and designated areas for different types of operations, such as fabrication and assembly, and areas for storage and transportation.
- A location with sea access, typically with a dock or slipway for transferring products between land and sea and quays to access products from land while seaborn.
- Ability to mount large assemblies and products in terms of space, equipment, and competence, whether at a dock, at the quay side, or in assembly halls and areas.

Following the general definition of manufacturing logistics cited in Chapter 2, yard logistics is here defined as *the coordination of the yard operations concerned with the flow of materials and information through the yard up to the production of the end product.* It entails the movement of the materials (components, parts, assemblies, and products), resources (including humans), and information required for producing and servicing large, complex, and customized products at a yard. Yard logistics uses input from non-physical processes, such as planning, design, engineering, and procurement, to support the execution of project plans for producing the end product.

In other words, yard logistics supports and facilitates efficient production (i.e., the production process). Accordingly, yard logistics activities are dictated by the production process performed at a yard, i.e., they depend on the stages of the production process that are performed at the yard. Irrespectively, the task of yard logistics is to support and facilitate the production process. Table 10 provides an overview and descriptions of the main activities of yard logistics.

Table 10: Overview and descriptions of the main activities of yard logistics.

Activities	Descriptions
Material reception	The physical and administrative tasks related to the reception of materials delivered to the yard from suppliers
Warehouse management	The tasks related to managing the main warehouse in terms of storing material, picking orders, registering incoming materials, and organizing the warehouse
Transportation and material movement	The internal transportation of material at the yard; the physical transportation as material is moved between storage areas and production or assembly areas; and the administrative aspects of the transportation, such as booking, generating, and reporting transportation jobs
Material control	The administrative tasks related to controlling the internal supply of material based on work package requirements (e.g., providing and using information on which equipment to use for material handling)
Work package coordination and distribution	The units of work at a yard are defined in work packages, and these require coordination and distribution to the operators (workers), typically performed daily by a yard's supervisors
Progress monitoring and reporting	The tasks related to monitoring and reporting of progress on the work package level (or the yard's lowest monitored level)

4.1.2 The constituents of yard logistics

Yard logistics refers to internal logistics in the yard context. In other words, it deals with the coordination of the yard operations concerned with the flow of materials through the yard until the completion of the end product. Accordingly, a yard logistics system is limited by the physical boundaries of the yard—a relatively large, geographical area compared to traditional manufacturing logistics contexts (e.g., a factory). As in any logistics system, the flow of materials is closely linked to the information flow within the system.

Material flow in yard logistics refers to the physical flow of materials (components, parts, assemblies, and products) through the yard. From the operative, internal view perspective on logistics, the material flow in yard logistics starts at the point the materials are received at the yard and continues through storage, between production stages, and until the materials are ready to leave the yard in the form of a completed product to be delivered to a customer. Efficient production is dependent on these flows.

Information is what triggers any action at a yard, including the flow of materials. How information flows internally in a yard is a key aspect of its yard logistics. This includes what type of information triggers actions, how this information is shared, which actors (operators, supervisors, managers, etc.) are involved in the information flow, and any information systems used to support the information flow.

We can distinguish between two domains within yard logistics: yard logistics structure and yard logistics control.

Yard logistics structure

The yard logistics structure refers to how the yard logistics system is set up in terms of how and where the material flows. To embrace it, we can define and distinguish between three constituents: product and materials; facilities, areas, and equipment; and layout.

Products and material make up the physical objects to be handled in the yard logistics system. The different businesses within yard operations mentioned in sub-section 2.2.1 produce and deliver different products and services. Accordingly, the materials that are handled at the yard may differ.

The extent of steelwork performed is one factor in this regard, as it adds requirements for the handling and storage of steel materials. Although steelwork is extensively automated in most shipyards, it requires both systems and space for handling and storing steel material (Bruce, 2021). Medium and large-sized shipyards involved in hull construction also need to handle large assemblies and blocks, requiring large-capacity cranes and vehicles (Bruce, 2021). With such physical objects being part of the yard logistics system, these yards have significant yard logistics activities related to the transportation of blocks to storage areas, between production stages, etc. (Jeong et al., 2018b).

As described by Semini et al. (2018), some yards predominantly perform outfitting, commissioning, and testing. The physical objects handled at yards focused on outfitting differ from those handled at yards that are heavily involved with steelwork. Accordingly, their logistics systems are more concerned with handling and moving piping, electrical components, HVAC components, and other system components, such as engines (Wei, 2012). Therefore, a significant amount of the yard logistics activities concerns the movement of both workers and tools to and from the places the outfitting work is performed (Rose et al., 2016).

Yards producing offshore maritime installations, such as topsides for fixed and floating oil platforms, require large amounts of outfitting (Gi Back et al., 2017). In essence, for outfitting topsides, the physical objects are comparable to those of outfitting in shipbuilding—requiring handling of many components to be installed and, therefore, a movement of workers and equipment to perform the installation jobs of the outfitting stage. Additionally, topside construction involves handling (especially lifting) large modules and decks during the different assembly stages. Other offshore products, such as steel jackets for oil platforms and offshore wind farms, do not involve outfitting to the same extent. However, the construction of such jackets, which may reach heights of more than 200 m, involve huge efforts related to the handling of large steel structures during fabrication and assembly of the jackets (El-Reedy, 2020).

Yards performing services perform work on, and handling of, an existing product. For yards performing services that involve low amounts of steelwork, such as repair and maintenance services, yard logistics involves handling smaller equipment and components, with less need for high-capacity material handling equipment. Yards performing services such as ship conversion are more involved with steel-related work, and thus the yard logistics at these yards may involve some handling of steel materials and structures (Sinha et al., 2005).

A yard's facilities, areas, and equipment, as well as their arrangement with respect to each other, also play a crucial role in determining the material flow. A site's layout should enable efficient flows of material while at the same time ensuring high space utilization (Jonsson, 2008). Due to the geographically large areas consisting of both buildings and outdoor areas as well as specialized facilities, such as docks, cranes, and quays, the internal transportation is comprehensive and covers large distances. Furthermore, there is a certain amount of rigidity in the placement of some of the facilities and areas, such as docks and quays, which has structural implications for how materials can flow through the yard.

Material flows both between facilities and areas (e.g., from the prefabrication facility to the outfitting area) and within or through the different facilities (e.g., material flows through the steel part production facility). The flow of materials in yards requires transportation and material handling equipment, both within the different facilities (e.g., overhead crane) and between facilities and areas, e.g., by different types of vehicles. The typical transportation and material handling equipment found at yards includes different types of cranes (e.g., level luffing jib cranes, goliath cranes, overhead cranes in buildings), conveyors, vehicles (e.g., self-elevating transporters, multiwheelers, rail-mounted vehicles, automatic guided vehicles, trucks, and vans), and different types of fork lifts (Bruce, 2021). Again, the types and amount of equipment needed at a yard is largely dependent on the type of material that needs transporting, considering the previously mentioned differences between medium and large shipyards (Jeong et al., 2018b), topside construction (Gi Back et al., 2017), jacket construction (El-Reedy, 2020), ship outfitting (Wei, 2012), and ship service (Sinha et al., 2005).

Yard logistics control

Yard logistics control concerns the control, or management, of both material and information within the given yard logistics structure. To support the production process at a yard—serving and utilizing the yard's facilities, equipment, and areas—the material and information flows must be controlled. Within the domain of yard logistics control, we can distinguish between two tightly integrated constituents: material management and work management (Woo & Song, 2014). These constituents describe how the main yard logistics activities (Table 10) are performed and what they entail.

Material management is generally defined as the "management functions supporting the complete cycle of material flow, from the purchase and internal control of production materials to the planning of work in process to the warehousing, shipping, and distribution of the finished products" (APICS). From an operative, internal logistics perspective, material management in yard logistics is about managing the storage and movement of materials within the yard (Bruce, 2021). It starts when materials arrive at the yard, which includes administrative tasks related to their reception, such as logging the receipt of materials, and is typically followed by moving the materials to a warehouse.

Managing stored materials is a key part of materials management in shipyards (Bruce, 2021). Stored items can be standard items, project-specific purchased items, or interim products, such as assemblies that are stored pending further processing. In addition to the typical main warehouse, there may be various other storage areas at a yard—outdoor or indoor—all of which require some sort of management depending on the items stored. For instance, a yard may have an intermediate storage for assemblies, such as large blocks (Jeong et al., 2018b). With the high volume and high mix of materials at yards, decisions related to how and where materials are stored are key decisions that affect yard logistics materials management. For instance, efficient utilization of a yard's available space is crucial (Jeong et al., 2018a).

Materials management further needs to ensure the internal supply of material from the yard's warehouse to the location where the material is to be used in production. In some cases, internal orders must be placed to book transportation with a certain type of transportation equipment.

Depending on the characteristics of the material, material management involves handling, transport, storage, sorting, location, and manipulation of any item in the yard (Bruce, 2021). Accordingly, materials handling makes use of the yard's equipment to move, lift, and store materials. Providing and using information on how and when to handle materials as well as information on which locations to move material from and to are all part of materials management in yard logistics.

As mentioned, materials management is closely integrated with work management, which is described below. The initiation of work at a yard triggers materials management activities required to supply the correct material to the place it is requested. Thus, efficient material flow requires that the control of yard logistics in terms of materials management and work management is well coordinated.

Work management involves managing the production work performed at the yard, including the workers performing the work, and the drawings and production documentation needed (Woo & Song, 2014). The production work performed is specified in so-called work packages, which define and describe the work and materials required in the various production stages. Work packages typically take the form of printed binders with documents, including drawings, bill of materials, and descriptions of procedures (Hagen et al., 1996). This is typical in shipbuilding as well as in offshore construction (Gi Back et al., 2017) and ship repair (Sinha et al., 2005). The work package is essentially an interface between design and engineering, where drawings and other documentation originates, and production and logistics.

Work management is usually organized in teams consisting of several workers and a supervisor (Bruce, 2021). The supervisor is responsible for coordinating the work packages and distributing them to the workers. Work management also includes progress monitoring and reporting of finished work, which are often done on the work package level (Bruce, 2021) and on a daily basis (Woo & Song, 2014). Progress monitoring and reporting on the work package level is critical for monitoring the overall project progress, which is essential for the yard to meet its contractual agreement with regard to the delivery date (Bruce, 2021).

From this analysis of yard logistics structure and control we extract five yard logistics constituents, presented in Table 11.

Table 11: Yard logistics constituents.

Yard logistics constituents	Definition	Descriptions
Products and materials	The physical objects handled in the yard logistics system	The physical aspects of logistics involve handling objects to move, store, sort, or manipulate them in any way. Accordingly, products and materials making up the objects in a logistics system is an important constituent of the logistics system. The physical objects in a yard logistics system may vary to a large extent depending on the end product delivered by the yard. Whereas some yards handle large blocks and even ship sections of several thousand tonnes, others mainly handle various types of equipment to be installed on a ship.
Facilities, areas, and equipment	The type and number of facilities at the yard and the type and amount of yard equipment related to the material flow	Yards differ in terms of what facilities, areas, and equipment they have. Facilities and areas can be differentiated between production and storage. Those for production are typically different types of prefabrication halls, assembly halls or areas, docks, slipways, and quays, while those used for storage include warehouses and outdoor storage spaces. Transportation and material handling move material within and between these facilities and areas.
Layout	The yard's physical arrangement of facilities, areas, and equipment	How different facilities, areas, and equipment are located relative to each other may greatly affect the efficiency of the yard logistics in general. Their arrangement within the yard's total area has implications for how the material flows around the yard.
Material management	Management of the storing and movement of materials within the yard	Material management in yard logistics starts from the arrival of materials at the yard and includes the following main activities of yard logistics as described in Table 10: material reception, warehouse management, material requisition, transportation and material movement, and material control.
Work management	Management of the production work performed at the yard (the workers and work packages)	Work management ensures the efficient flow of the information required to perform production work in a yard. It includes work package coordination and distribution and progress monitoring and reporting, as described in Table 10. Work management is closely linked to material management because the initiation of a work package initiates material requirements.

4.1.3 Key characteristics of yard logistics

The case findings include a set of key characteristics of yard logistics, relating to both structure and control, which are described in the following paragraphs.

Large sites

As geographically large sites, there are often long distances between facilities and areas. For some yards, this results in long walking distances for workers, for example, when walking from the quayside to the warehouse to pick up something and back, as was observed at Case yard J. For other yards, their size results in long internal transportation routes from storage areas to the different facilities, such as at case yard C. Either way, the large sites are characteristic features of yard logistics.

Storage

The storage of materials is an important aspect of yard logistics. Stored materials may include standard items required for all projects, project-specific parts, and assemblies intermediately stored between production stages. Moreover, certain items may require indoor storage facilities for protection from weather, while others can be stored in outdoor areas. Independent of the yard size and type of yard operations, storage areas and stored materials make up a significant amount of a yard. With such comprehensive storage of materials on-site, it is crucial to efficiently manage both the stored materials and the way in which the storage areas are operated.

Organization in departments

The findings from case study V indicate that a key aspect of yard logistics control is the extent of departmentalization of the yard operations, that is, the degree to which the yard operations are organized in departments. A common differentiation indicated by the empirical data is between production and warehouse departments, while some yards also have a separate department for internal transportation. For larger yards with a more comprehensive production process, production may also be split into different departments (e.g., prefabrication, assembly, and outfitting). When organized in departments, each department has its own operations manager and a set of supervisors. In practice, this means that yard logistics activities are performed by several departments. Given the nature of the products produced at yards in this context (large, customized, and complex products requiring coordination across the production stages), the organization into departments intensifies the need for and importance of cross-department coordination. For the most departmentalized yards, this type of coordination represents a significant part of daily operations. Conversely, some yards have a looser department structure (warehouse and production). This can enhance synchronization, but it compromises the structure and distribution of responsibility.

Work packages

The main "information packages" in yard logistics are the work packages describing each job. Work packages and accompanying documentation are provided to operators, who execute the work, on a daily basis. This distribution is often physical, in the form of printed documentation in binders, although some yards are investigating IT-based solutions to distribute work packages. Work packages can also be considered as the information that triggers production work. Typically, every morning the different supervisors distribute work packages to their operators, and this acts as the signal to initiate work.

People

Independent of yard type, yard logistics executed by people. Supervisors are responsible for distributing work packages to operators, and operators are responsible for executing the work described. In contrast to the other extreme in manufacturing, the process industry, which can nearly be run without human intervention—yard logistics requires people involved at all stages. This means that efficient yard logistics is dependent on the operative communication among supervisors and operators, their interpretation and understanding of the information provided to them, and their ability to make decisions related to yard logistics.

Due dates

Production is controlled based on the due dates set for each work package. The due dates are set by higher-level departments, often the engineering department, based on a work breakdown structure. In production, work packages are released and assigned to operators based on which job is most urgent, as indicated by the due date and the extent of the work package. Apart from the supervisors' experience and gut feeling, the work package due dates are the key variable that informs decisions related to releasing the work package.

Workstation reorganization and preparation

Yard logistics must also take into consideration the need for workstation reorganization and preparation between work packages. The high level of customization and the uniqueness characterizing much of the work performed at a yard lead to a low degree of repetitiveness of work that is carried over to single work packages. Accordingly, the start of work on a new work package often requires reorganization and preparation, such as collecting the proper tools and equipment, before the value-adding activity can commence. It is crucial to maintain awareness and consideration of this point to ensure efficient yard logistics.

Reporting

A final key characteristic of yard logistics is reporting, or progress reporting. Again, the nature of the products produced at the yards in this context (large, customized, complex products with a relatively long throughput time), requires that progress is monitored continuously to determine whether the project is progressing according to plan. The overall monitoring of project progress can be broken down to progress on the work package level, where supervisors and operators are the key actors. As such, a key responsibility for them is to report the progress on work packages, making progress monitoring and reporting a comprehensive activity. All eight of the yards involved in case study V perform progress reporting manually on a weekly or bi-weekly basis for the completed work packages.

4.1.4 Characterization of yard logistics according to yard operation type

With the general understanding of yard logistics provided in the preceding parts of this section, it is possible to categorize different types of yard operations. Such categorization adds further structure to the knowledge on yard logistics, enabling descriptions of yard logistics according to the types of yard operations. Case study V enabled the identification of three different types of yard operations: fabrication operations, outfitting operations, and service operations (Figure 8).

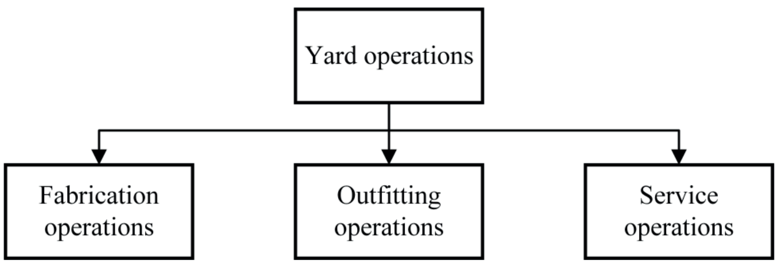

Figure 8: Yard operation types.

The existence of different yard operation types is a key factor in understanding yard logistics, as aspects of the yard logistics constituents as well as typical yard logistics challenges can be linked to the type of yard operation. This link is explored in the following paragraphs, with further details in paper 1.

From the empirical data collected in relation to paper 1, it was possible to describe yards dominated by either fabrication operations, outfitting operations, or service operations. All the operation types are present to some extent at each of the case yards. However, the yards are typically *dominated* by one particular operations type. This dominant type can serve as the basis for a logistics-focused description of the different yard types, provided in the following paragraphs and summarized in Table 12.

Fabrication yards

Fabrication yards are involved in offshore construction, producing oil platforms, modules, and other offshore structures. They are characterized by being very large in size, both in terms of total yard area and the number of yard workers. Part of this is due to the large scope of production stages at this type of yard, ranging from the processing of steel plates and profiles and the prefabrication of pipes and steel structures to several stages of assembly (sub-structures and end products) and outfitting. This requires a range of facilities, including production halls and areas and warehouse and storage areas, adding to the yard's total area. Moreover, fabrication yards work on large, complex projects involving thousands of parts and components. This leads to comprehensive material management and handling, including the reception, storage, and transport of the materials that go into each end product. Therefore, fabrication yards have a high number and wide range of transportation equipment to transport heavy parts, assemblies and structures, and materials in high volumes. The material management at fabrication yards is significantly more comprehensive than at service and outfitting yards, requiring large efforts in warehouse operations and material handling. This large operation requires a large area to contain all the required facilities, and the number of yard workers is also high.

Fabrication yards have a strict division in departments, with separate departments for warehousing, transportation, and for various production stages, areas, and disciplines. This provides a clear division of responsibilities and tasks and ensures structured operations, although it requires significant cross-functional coordination between the different departments to maintain synchronized production. It is evident from the empirical findings that there is some silo thinking present at these larger fabrication yards, as each department tends to focus on its own progress, possibly hampering the overall efficiency and holistic progress of the yard.

With at least two to three projects at the same time, fabrication yards need both inter-project coordination (i.e., coordination between projects) and intra-project coordination (i.e., coordination within each project) for efficient operations. The projects are large, spanning 12–24 months, each with a defined project organization to run and coordinate the project. This organization includes a material coordinator, who is responsible for material management for the project. The internal coordination activity must be coordinated with one or two simultaneous projects at the yard.

Outfitting yards

Outfitting yards, as the name suggests, perform outfitting operations on new ships, where the ship hulls have been built at other yards. Accordingly, hull structures are brought to the yard and placed in a dock and/or at a quayside to be outfitted and completed for delivery to the ship owner. This has implications for the yard and its yard logistics. The focus of the yard logistics is on the dock and/or the quayside, and the main flows are to these areas from the yard's main warehouse or from various outdoor storage spaces. Yard logistics is therefore primarily concerned with managing the flow of materials and workers between these areas and onto the ship, whether it is in the dock or at the quayside.

Outfitting yards are significantly smaller in terms of their total yard areas than fabrication yards. For instance, outfitting yards do not need a dock to perform outfitting operations, although it adds flexibility and allows the yard to perform some additional tasks, which would otherwise have been performed at the hull yard. Not having a dock naturally reduces the total yard area. Nevertheless, the projects performed at outfitting yards are relatively large in terms of man hours, and consequently they have a long throughput time. Projects typically spend between 12–24 months at an outfitting yard, and the number of workers at this type of yard is higher than at service yards. With such large projects being carried out, outfitting yards typically have only one or two simultaneous projects. There is less need for inter-project coordination but a significant need for intra-project coordination.

Service yards

Service yards tend to be the smallest type of yards based on our empirical investigations. These are yards that, as their main operation type, perform maintenance, repair, conversion, upgrade, retrofit, and refurbishment jobs on existing ships. The scope of their yard logistics activities is narrow, related only to the types of service jobs described above. In practice, there is little steelwork or fabrication that occurs at these yards and very limited outfitting operations. Accordingly, there is a limited need for production and storage facilities, as each project involves a small amount of work compared to projects performed at other types of yards. A project at a service yard typically lasts 2–4 weeks, during which a ship is placed in the yard's dock or at the quayside to be worked on. With this relatively short throughput time for projects, the material turnover rate for materials stored on-site is high. Accordingly, the need for material storage space is limited. By utilizing all the areas to place a ship, the service yards are able to run several projects simultaneously, for example, by placing one ship in the dock and one at each of their quays. Accordingly, yard logistics at service yards is mainly concerned with handling smaller volumes of materials flowing onto and off the ships being worked on. A key aspect of this is the coordination of these simultaneously run projects, in terms of distributing workers to the different projects. Service yards typically have a loose division of departments, which allows for a flexible approach to this coordination and can enhance synchronization. Thus, they can quickly redistribute workers as needed, although it may result in an unclear and unstructured distribution of responsibility for the different tasks.

Table 12: Description of the different yard types.

Yard types	Description
Fabrication yard	• Large in terms of the total yard area, number of workers, number and diversity of equipment, and number and size of facilities • Wide scope of yard logistics activities, as production includes steel processing, prefabrication, and several assembly phases • 1–3 projects per year and 2–3 simultaneous projects at the yard requiring both inter-project and intra-project coordination • Comprehensive warehouse operations and material handling, as the yard handles large volumes of materials for all production stages • Yard logistics is primarily concerned with managing the flow of materials rather than workers because workers are designated to each facility/discipline, working in their respective areas, and because storage and transportation are separate departments
Outfitting yard	• Significantly smaller than fabrication yards, with a smaller total yard area and fewer workers and facilities • Medium/narrow scope of yard logistics activities (only activities related to outfitting, because the hull is built abroad), which reduces the number and size of certain facilities and equipment compared to fabrication yards • Coordination of up to two ships simultaneously, thus, intra-project coordination is mainly required, although there is some inter-project coordination • Projects spend between 12 and 24 months at outfitting yards • Yard logistics is primarily concerned with managing the flow of materials and workers between warehouse or outdoor storage spaces and the dock or quay—and onto the ship, whether it is in the dock or at the quayside
Service yard	• Smaller in size, in terms of the total yard area, number of production workers, number and diversity of equipment, and number and size of facilities at the yard • Narrow scope of yard logistics activities (only activities related to service jobs—no outfitting, no major steelwork, etc.) • Intra-project coordination of many small, simultaneous projects—typically between 3 and 6—and a total of several tens of projects each year. • Projects typically last 2-4 weeks. • Yard logistics is primarily concerned with handling small-sized materials in lower volumes on and off ships in the dock or at the quay as well as coordinating the range of jobs and workers across the yard's ongoing projects

Following this general description of yard logistics within the different yard types, we can apply the yard logistics constituents to structure a more extensive and comparative description of the yard types (Table 13).

Table 13: Yard logistics constituents for each yard type.

Yard logistics constituents	Fabrication yard	Outfitting yard	Service yard
Products and materials	Steel plates and profiles, steel components and structures, large assemblies, large number of components and systems to be installed during outfitting	Large number of components and systems to be installed during outfitting	Smaller number of components and systems to be installed during ship service, waste material
Facilities, areas, and equipment	Large quays (for mooring and load-out), dry dock	Dock (dry or floating) and/or mooring quay	Dock (dry or floating) and/or slipway, mooring quay
	Large main warehouse, several smaller warehouses, several large outdoor storage areas	Typically, one main warehouse and one smaller warehouse; several outdoor storage areas	Typically one main warehouse, one smaller warehouse, and some small outdoor storage areas
	Assembly halls (pre-assembly and assembly), prefabrication halls (steel and piping), surface treatment hall	Fabrication halls and workshops (steel workshop, outfitting workshop, mechanical workshop, pipe prefabrication hall)	Only smaller fabrication halls and workshops, typically steel workshop, mechanical workshop, and pipe workshop
	Main equipment includes gantry crane, tower cranes, mobile cranes, multiwheelers, transport wagons, trucks	Main equipment includes dockside and quayside cranes, tower cranes, trucks	Main equipment includes dockside and quayside cranes, trucks
Layout	Widespread, covering a large area, with facilities spread around inland from the quaysides.	Semi-compact, with facilities located near the dock and/or the quay.	Compact, with a few facilities located around the dock and/or inland from the quay
	Characterised by large open storage areas, outdoor assembly areas dominated by several large production halls and facilities, as well as long quaysides	Characterised by several smaller workshops and storage areas, dominated by a dock and a quay as the main facilities	Characterised by smaller workshops, dominated by a dock, quay, or slipway as the main facility

Material management	Material flows between warehouse/storage areas and production facilities (prefabrication halls, surface treatment hall, assembly areas, dock, and quays)	Material flows from warehouse/storage areas to the dock/quay. Materials brought onto ships by hand or by cranes	Main material flow from warehouse to dock/quay. Materials are brought onto ships by hand or cranes. There is a need to manage reverse flows of waste material (off ships) for some projects.
	Material flows controlled by material coordinators for each project, who send orders to the warehouse for the internal transportation of material	Material flows are controlled through material requisitions from production (supervisors) to the warehouse	Material flows triggered by workers when starting work on a work package that is distributed by a supervisor
	Separate transportation department executes internal supply orders received from material coordinators; some fixed routes and some use of dedicated zones for intermediate storage in several areas of the yard	Some principles for material movement, with some use of dedicated zones for intermediate storage prior to outfitting; uncomplicated but non-fixed routes for material transportation	No specific principles for material movement, which are decided ad hoc based on practicalities such as the size and weight of the items to be transported; uncomplicated but non-fixed routes for material transportation
	Comprehensive use of scaffolding, mobile and fixed platforms to support the flow of workers and materials during assembly	Comprehensive use of ramps and scaffolding to support the flow of materials and workers onto ships in dock or at quayside	Simple use of ramps to support the flow of materials and workers onto ships in dock or at quayside
Work management	Structured work management, with information sharing in daily meetings between supervisors and workers; cross-functional coordination meetings between different departments several times a week	Semi-structured work management with information sharing between supervisors and workers, often through daily morning meetings. Weekly meetings concerning production progress per discipline	Unstructured, ad hoc work management based on experience, gut feelings, and due dates, with supervisors coordinating and distributing work to operators; only occasional and manual/oral reporting of progress (for larger projects)
	Work package documents made available through digital solutions (smartphone apps or tablets), but also often distributed physically	Physical distribution of work package documents to workers	Physical distribution of work package documents to workers
	Work packages and their objects are linked to the internal manufacturing execution system, updated upon work package completion or change of status	Limited usage of IT systems for work management	Low usage of IT systems for work management
	Split in departments and disciplines, where departments and disciplines are organised as separate work management units	Production is typically split into disciplines, often organised as separate work management units; production halls (e.g., pipe prefabrication halls), if any, may also be organised as separate work management units	Production may be split into disciplines organised as separate work management units but not typically split into separate departments

4.1.5 Yard logistics challenges

A specific purpose of case study V was to identify yard logistics challenges. Certain improvements in yard logistics performance can only be realized by overcoming current challenges, which might not always be obvious.

Yard logistics challenges were found in several areas: material reception, space and storage needs, warehouse management, material management, material handling, material flow, transportation, coordination, work management, walking time, information flow, and mobilization of human resources.

To some extent, the challenges vary across different types of yards. Within some of the challenge areas, each yard type has similar challenges, but with varying extents. While for other areas, challenges are different in nature. The yard logistics challenges identified for the three yard types are shown in Table 14.

Table 14: Yard logistics challenges for each yard type.

Challenge area	Fabrication yards	Outfitting yards	Service yards
Material reception	Challenges related to handling the high volumes of incoming materials to the yard; the preferred sequence and times of delivery are not always achieved and thus must be moderated by yard logistics	Challenges related to the reception of large, project-specific deliveries, such as ship accommodation facilities, that can disrupt the storage needs at the yard	Frequent, irregular deliveries from suppliers can cause challenges with regard to maintaining a structured and tidy warehouse
Space and storage needs	Large storage needs (in terms of both material size and volume) for most projects leads to large storage space needs, which results in large distances between materials stored on site and processing areas Additional challenges relate to large variations in storage needs from project to project	Large variations in storage needs from project to project often lead to temporary storage solutions, potentially creating inconsistency in storage locations	Large variations in needs for storage space from project to project cause some challenges with regard to storage; however, the volumes and item varieties are quite manageable Storage space needed for waste materials from ships
Warehouse management	The high volume of materials stored requires comprehensive warehouse operations, and it can be challenging to find available space	Challenges related to efficient storage in the main warehouse, especially handling both standard items and project items interchangeably	Highly manual storage operation Challenging to find efficient principles for warehouse management that fit all situations because service projects may vary in terms of the extent of work and materials needed. With no principles applied, warehouse management becomes unstructured and inefficient.
Material management	Ad hoc material management causes challenges with intermediate storage (between warehouse and place of use) because of untimely material requisitioning from storage to production. The requisition of materials to production must not be done "too early," as this causes materials to pile up in production. This intermediate storage can become too large and difficult to manage The high variety and volume of items results in challenges related to knowing what material is at the yard and where it is; this can result in time spent searching for specific items	Ad hoc material management causes challenges related to knowing when to move materials from storage to the dock or quay, in which sequence according to the sequence of outfitting tasks and where to put it, potentially causing piled up materials that are intermediately stored in the dock or at the quay The high variety and volume of items leads to challenges related to knowing what material is at the yard and where it is; this can result in time spent searching for specific items	Lack of principles for requisition from the warehouse No particular challenges related to knowing where things are (as there are not that many places where things can be and not many materials)

Challenge area	Fabrication yards	Outfitting yards	Service yards
Material handling	The yards handle physically large items, requiring high-capacity transportation equipment that requires space for maneuvering. This leads to a need for open spaces, resulting in large distances and lowered space utilization	Outfitting ships in a dock or at a quayside causes challenges related to getting people and materials on/off the ship during outfitting, especially for the outfitting that is done when the hull structure is closed; accessing different levels/decks of the ship in the dock and at quayside is a challenge	A significant part of logistics concerns handling waste materials, including storing and sorting these materials
Material flow	Some jumbled flows in certain departments and production halls, such as the prefabrication hall; often, materials enter and exit through the same gate, making it difficult to streamline the material flows Not always possible to work on the most critical jobs because there is often time needed for setup between each larger component entering the hall, which is filled with smaller jobs somewhat randomly so that there is work to do	High-volume, high-variety material flows make it challenging to find solutions for efficient material flow	Waste materials taken off ships add an opposing material flow in addition to the flow of new materials onto the ship, which it might disturb Large variations in material volume and material flows
Transportation	Amount of transportation of units around the yard is significant, and units must often be brought back to storage because there is no available space in front of the processing site, (e.g., the paint shop); this results in a high number of transports per unit, many of which are unnecessary (back and forth between storage without being processed)	Transportation does not pose any particular challenges	Transportation does not pose any particular challenges

Challenge area	Fabrication yards	Outfitting yards	Service yards
Coordination	The main challenge is interproject coordination of several large projects running simultaneously; coordination is required with regard to the yard's physical resources and equipment (i.e., which project will occupy which resources when), but it may be difficult to avoid silo thinking within projects There may be additional challenges related to coordination between departments (i.e., pipe fabrication and assembly); every department has its own production plan, making synchronization across departments a challenge	The main challenge is intra-project coordination of the disciplines performing outfitting work; coordination is required to ensure that the installation sequence is followed and that work within the different disciplines does not conflict	The main challenge is short-term, interproject coordination of activities and people (i.e., allocating workers and tasks to the different service projects running simultaneously). This entails knowing that materials are available for different projects. They need to coordinate 80–90 people, all working on several projects and performing multiple activities every day. People may be moved between projects on a daily basis, depending on what is most urgent.
Work management	With the ad hoc approach to work management, the yards rely heavily on individuals in most daily decisions related to work management, which are largely based on experience, gut feelings, and tacit knowledge		
Walking time	Walking times are not a significant challenge because workers are typically working within one area (e.g., in the warehouse or a specific production hall). However, in large areas, such as assembly areas, there may be considerable walking distances.	Workers need to spend time walking between different areas, primarily between the dock/quay and storage, as they have tasks in several places; distances can be significant, even at the smallest yards	There is no particular challenge with regard to walking times; workers walk between different areas, but the distances are not significant
Information flow	Comprehensive IT systems with fair support for yard logistics; however, feeding and extracting information must often be done manually because the systems are not tightly integrated	Only some IT system support for yard logistics, but integration between them is difficult, and they are mainly standalone systems; many administrative tasks are manual	There is no IT systems supporting yard logistics, meaning that many administrative tasks are performed manually, including unnecessary non-value-adding time spent on manual registrations and list writing
Mobilization of human resources	Longer term (months and years) mobilization and demobilization of a high number of people for new projects; providing facilities and accommodation for these resources may be challenging	Medium-term (months) mobilization and demobilization of human resources for new projects; providing facilities and accommodation for these resources may be challenging	Short project durations require short-term (days) mobilization and demobilization of human resources—up to 100 people—a crucial but challenging task

4.1.6 Yard logistics performance

A key aspect for efficient logistics management is measuring logistics performance. First, this requires identifying and establishing the most relevant measures. The relevance largely depends on the particular context they are to be used in, as the appropriateness of different performance measures differs between manufacturing environments (Gunasekaran & Kobu, 2007). Therefore, paper 2 sought to investigate the yard logistics context to further identify the most relevant performance measures for yard logistics. Second, the paper evaluated how the identified measures can be applied in practice in a yard logistics context.

The distinct challenges of the yard logistics environment have implications for measuring yard logistics performance. Case study V identified the following important aspects when designing a yard logistics performance measurement system:

- Yards are physically vast areas, often resulting in long walking distances for operators, who must move inside and between production, assembly, and storage areas:
    - Non-value-adding time spent walking
- Yard operations are typically organized in departments, such as, warehousing, transportation, fabrication, and assembly, and thus often lacking a holistic view of the yard's operations:
    - Suboptimal overall logistics performance
- There are significant amounts of material transports around the yards (often with long transport distances and many "trips") and inefficient flows of materials between storage areas and point of use:
    - Non-value-adding time spent transporting material
- Yards have several large storage areas for stockkeeping components and parts (deliveries from suppliers occupy space, deliveries ahead of schedule, etc.) and work-in-process sub-assemblies:
    - Large inventories and materials spend a long time in storage
- A key characteristic of yard-produced products is long throughput times—both for end products altogether and individual components in isolation:
    - Large amount of work-in-process material
- The low degree of repetitiveness in production requires workstations to be reorganized and prepared for each new job:
    - Non-value-adding time spent preparing workstations

The following principles were applied in the development of a performance measurement system for yard logistics:

- Based on existing performance measures from the academic literature
- Adapted to the context (based on case findings)
- Possess features of effectiveness (Afy-Shararah & Rich, 2018):
    - Reflects the overall strategy of the organization
    - Provides a foundation for communication between stakeholders
    - Diagnoses reasons for the current situation
    - Detects abnormalities to trigger learning and improvement
- Measures should be acceptable, suitable, feasible, effective, and aligned (Jonsson & Rudberg, 2017)

The set of performance measures identified, developed, and defined is presented in Table 15.

Table 15: Performance measures for yard logistics.

Performance measures	**Definition**	**Measurement approach**	**Source**
Requisition lead time	Lead time to requisition work package material from the warehouse as a percentage of total work package completion	Measure the time elapsed from when an order is sent to the warehouse to when the order is ready to be moved from the warehouse	Adapted from Sjøbakk et al. (2015)
Production time lost	Production time lost because of unavailability of materials	Measure the time from when a job is scheduled to start to when the material has arrived; operators register their jobs when they are ready to start them and register them again when materials have arrived for the job	Adapted from Sjøbakk et al. (2015)
Internal delivery precision	Warehouse deliveries received on time at place of use	Deliveries from warehouse to place of use are registered upon delivery; the actual arrival time was matched against the scheduled arrival time	Adapted from Sjøbakk et al. (2015)
Transport efficiency	Number of transports per unit	Each unit that is scanned/registered for data registration purposes will get one more "number of transports" each time a new transportation order is issued for that unit	Own development
Put away cycle time	Time elapsed after incoming materials are delivered to the yard until they are put away in the warehouse	Materials are registered upon arrival at the yard and again when put away in the warehouse	Adapted from Kusrini et al. (2018)
Order picking cycle time	Average order picking cycle time for internal orders placed to the warehouse	Measure the time from order picking is started (i.e., registered by a warehouse operator) until the order is ready for transportation out from the warehouse (also registered by the warehouse operator)	Adapted from Kusrini et al. (2018)
On-time work package completion	Percentage of work packages completed by the due date	Operators register their work packages when completed, and the time stamp is checked against the due date	Adapted from Telles et al. (2020)
Information quality	Amount of perfect work package descriptions	For each completed work package, the operator registers whether additional information apart from the work package description was required to complete the work package	Own development
Operator efficiency/ productivity	Operators' non-value-adding time	Operators register their time spent on value-adding work, which is subtracted from their total working time to find the time spent on non-value-adding activities, such as walking, waiting, searching	Adapted from Thomas and Daily (1983)

As a means to reduce the time spent on material requisition for work packages, this time should be measured. In an ideal just-in-time situation, material for work packages should be ordered from the warehouse when they are needed. Accordingly, short material requisition times would be desirable. Knowing how much of the total time required to complete a work package is spent on administrative and material transportation-related activities before the material is consumed in the execution of the work package can create awareness of this type of non-value-adding time.

Related to the measure of requisition lead time, an additional measure may specify the actual production time lost waiting for materials to arrive. If operators register their preferred starting time for each job as well as when the required material arrives, the time lost waiting for material can be determined. Ideally, this will highlight efficiency challenges related to the supply of materials to operators executing work packages.

Internal delivery precision can be used as a measure to improve warehouse and internal transportation operations. Internal deliveries include the materials required for the execution of work packages in the production or assembly areas of the yard, to which the materials are brought from the warehouse. By registering and comparing actual arrival times of internal deliveries with the scheduled arrival time, the yard can determine the percentage of deliveries that are on time. A low percentage will indicate challenges related to the overall efficiency of the warehouse and transportation operations, and this measure can be used to guide improvement actions.

To address the issue of unnecessary transportation of single units, the number of transports should be measured. Especially at larger yards, yard logistics includes the movement of larger units (subassemblies and larger parts) between storage and different production or assembly areas. Unnecessary movements, where units collected at the storage location are returned to storage unprocessed due to unavailable space or capacity at the time of the transport, may occur. Counting the number of transports for each unit may be useful in this case. While this measure may require further analysis to identify the root causes, it will create awareness of a potential source of unnecessary non-value-adding transportation time.

Another measure related to warehouse operations is the put away cycle time for incoming materials delivered to the yard. Upon arrival at the yard, these materials are put away in the internal warehouse, ready for further internal distribution. Measuring this cycle time can help to identify the potential for reducing this type of material handling activity, thus improving the efficiency of warehouse operations.

In the next step of warehouse operations, the order picking time for internal orders sent to the warehouse may be a source of unnecessary non-value-adding time. To address this, the time spent on this operation could be measured. In practice, a warehouse operator will register when the picking of an order is started and when the order is picked and made ready for transportation from the warehouse. This will give a measure of the time spent on order picking and might help to identify actions that are needed, for example, to improve the efficiency of the internal flow and material handling in the warehouse.

For work package execution, a relevant measure may be on-time work package completion. Each work package has a preset due date, which should be used as a measure of completion precision, that is, the percentage of work packages completed by the due date. In practice, this will only require the registration of work packages when completed, with the time stamp checked against the due date to determine whether or not the work package was completed on time.

To address the importance of work package descriptions—the information required by operators to execute work packages—one performance measure should highlight information quality. To avoid time spent seeking or requesting missing information, the yard can facilitate that operators register whether or not the work package description is sufficient, for each assigned work package. This measure could create awareness of issues regarding the preparation of work packages, which is key to the efficient execution of work, without such unnecessary non-value-adding time.

The final measure concerns operator efficiency. In addition to the time spent collecting additional information related to work packages, operators often spend time searching for materials, walking to collect equipment or tools, and performing other non-value-adding activities required to execute work packages. To identify these sources of waste, this time should be measured and compared with the operators' total working times.

Although the suggested yard logistics performance measures are intended to be universally applicable, there may be individual differences among yards and between different yard types. Accordingly, it may be necessary to adapt, remove, or add certain measures depending on each specific yard environment or for each yard type. However, the process of identifying and developing the described measures can be based on certain general guidelines for the performance measurement system design process:

- Follow generic principles for performance measurement system design
- Pay attention to context characteristics

- Take a holistic approach to the development of performance measures

A key issue related to the practical implementation of these measures is their feasibility. Regarding technological feasibility, they have all been determined to be within the already-existing capabilities of the yard's IT infrastructure. Hence, implementation would not require any significant upgrade of the current IT infrastructure. However, it must be noted that increased measurement would increase the number of registrations required at the yard. These types of registrations (e.g., updating the status of an order in the internal IT system for production) should be implemented in such a way that one can avoid that performing the registrations become a source of waste itself.

The suggested performance measures do not specify whether registrations should be done manually or automated by some type of technological solution for scanning, etc. While automation of these registrations would be desirable from the perspective of time efficiency, further investigation is needed to determine their cost-efficiency. In the case of manual registrations, the tradeoff between the time spent and the benefits of the measurement must be assessed. In any case, it is important to identify and establish the most appropriate, suitable, and effective measures before any measurement process is implemented and, possibly, even automated. Nevertheless, moving towards digitalization provides excellent opportunities to apply automated measures related to yard logistics.

4.1.7 Factors affecting yard logistics

A key for developing knowledge and understanding of yard logistics is awareness of the contextual factors that define the environment in which the yard logistics occurs. These factors can be referred to as the manufacturing environment or the planning environment (Jonsson & Mattsson, 2003). In studying the yard logistics context, the yard logistics environment is defined as the internal and external factors that affect yard logistics activities, based on the definition of manufacturing environments provided by Buer et al. (2018b).

Paper 3 aimed to investigate the factors affecting yard logistics. Based on a review of the existing literature, a set of four main factors were identified, each containing a set of variables, or items. This enabled the construction of a framework that can be used to map and describe yard environments. The framework is presented in Table 16.

Table 16: Factors affecting yard logistics.

Factors	Items	Content	References
Yard characteristics	Yard facilities	Main production facilities, docks, and quays	Colin and Pinto (2009)
	Yard equipment	Main yard equipment for material handling	Pires Jr et al. (2009)
	Yard size	Total number of shipyard workers, total yard area	Lamb and Hellesoy (2002)
	Yard layout	Shape and direction of material flows through the yard	ECORYS (2009)
	Automation level	Level of automation of the production process	Colin and Pinto (2009)
	IT level	Level of IT systems infrastructure and integration	Pires Jr et al. (2009)
Product and market characteristics	Vessel types produced	Tankers, bulk carriers, cargo/passenger ships, fishing vessels, offshore vessels	Eyres and Bruce (2012)
	Customization	Degree of customization	Semini et al. (2014)
	Total production volume	Average number of vessels produced per year	Buer et al. (2018b)
	Order size	Average number of similar ships per customer order	Buer et al. (2018b)
	Type and size of market	Type and size of the market the shipyard competes in	ECORYS (2009)
Process characteristics	Throughput time	Average throughput time of a customer order	Buer et al. (2018b)
	Main production process stages	Main stages of the production process performed at own shipyard	Semini et al. (2018)
	Building practices	Degree of advanced outfitting	Eyres and Bruce (2012)
Supply chain characteristics	Supply network	Characteristics of the supply network	Pires Jr et al. (2009)
	Vertical integration	Shipyard's integration with hull yard, ship designer, main equipment suppliers, shipowner	Lamb and Hellesoy (2002)

As shown, the framework includes four main factors. Each factor consists of a number of items, or sub-factors, which are described in the following paragraphs.

Yard characteristics

The first factor, yard characteristics, recognizes some of the differences between yards and the traditional production systems of factories. Accordingly, this factor includes the yard's facilities and equipment, size, and layout, as there are large variations between yards with regard to these sub-factors. Yard size includes both the total yard area and the total number of shipyard workers. Maritime yards produce large-scale products that require space during production. The internal movement of materials, products, and workers across the yard is a key aspect of yard logistics, and thus it is included in the framework. The total number of shipyard workers is included to capture the importance of the workers in such a highly manual manufacturing context. The workers perform large parts of the work at a yard; hence, the total number can be significant.

Compared to traditional factories, yards have an unusual nature, with several facilities and outdoor spaces for storage, production, and assembly. Yard operations also require special facilities for docking as well as quays. The yard structure largely defines the activities that are performed and is thus significant for yard logistics.

Yards in this context predominantly apply a fixed-position layout type for the end products. However, the yard layout sub-factor is more complex than a determination of the basic layout type, as there may be different variations of the fixed-position layout. Furthermore, yards may have elements of other basic layout types in different areas of the yard. How facilities are located relative to each other determines the shape and direction of the material flows through the yard. Therefore, yard layout is included as a sub-factor of yard characteristics that affects yard logistics.

The level of automation of the production process will primarily affect production but is included as different levels of automation may cause differences in the yard logistics activities that support the production process, for example how and where material should be supplied. Finally, the yard characteristics factor includes IT level, here defined as the yard's IT system infrastructure and integration. This is considered a key non-physical support for yard logistics activities. The execution of logistics activities is controlled by the information that triggers actions, and the IT system infrastructure and integration facilitate that flow of information. Hence, it is included as the final sub-factor of yard characteristics.

Product and market characteristics

The variables typically used to describe product and market characteristics include CODP placement, production volume, product variety, customization, product complexity, and demand characteristics (Buer et al., 2018b). Adapting these to the yard environment results in the sub-factors vessel types produced, customization, total production volume, order size, and type and size of market.

Yards can vary based on the type of products they produce. Products vary in size and complexity, and these variations can impact aspects such as the material handling equipment needed, how yard activities are organized, and the general complexity related to the yard logistics.

The degree of customization of the products impacts several aspects of a yard's supply chain, including the internal logistics. Further, it impacts the potential to standardize operations. Thus, yard logistics can be affected in terms of storing and warehousing material, material handling and transportation, and logistics related to the production process, such as preparing workstations for new jobs.

Total production volume, measured by the average number of vessels produced per year, is a sub-factor that provides information about the operations at a yard. There are large differences between yards with regard to their yearly production volumes of end products—ranging from less than one product per year on average to several tens of products. Higher volumes require handling of several projects simultaneously, thus greatly impacting yard logistics activities.

Yards may or may not produce ships in series. Many shipyards are specialized in building single, highly customized products, while others produce higher numbers of similar ships, possibly with a high level of customization of the entire series. For series production, it is more rational to establish dedicated lines and streamline and standardize the material flows than it is in the case of one-off production. Hence, order size is included as a separate sub-factor of the product and market characteristics.

Finally, as product-related characteristics such as customization, vessel type, production volume, and order size are tightly interlinked with market characteristics, the final sub-factor is type and size of market. Certain markets are associated with more specialized, and therefore often more customized, products, while other markets rely on a higher volume of more standardized products. Accordingly, the type and size of the market a yard supplies to has an impact on yard logistics.

The sub-factors of product and market characteristics must be seen in relation to each other. A high level of customization can lead to challenges in yard logistics, as the logistics system needs to handle a customized project for which efficient logistics solutions may not be in place. However, a large order size for a customized product may keep complexity at a manageable level, allowing the shipyard to adapt high-volume principles to the logistics related to an order of a number of similar ships.

Process characteristics

The process characteristics factor describes the key aspects of the physical production process at a yard. It includes the sub-factors main production process stages, throughput time, and building practices.

Shipyards commonly offshore certain stages of the shipbuilding process. This is the typical approach in certain European countries, where labor costs are high. Therefore, the labor-intensive steelwork related to the construction of the hull is outsourced to lower-cost countries. Accordingly, in mapping yards, the main production process stages performed at each yard should be described. In contrast, many other shipyards perform all production process stages at their own yard. The scope of production process stages covered at each yard directly impacts the related yard logistics activities and is therefore included as a sub-factor in the framework.

Throughput time is a common measure in logistics in general and describes the amount of time a product spends at a site. For yards, it is of interest to know the time each ship spends at the yard on average, as it occupies both space and resources. Throughput time also gives an indication of how yard operations are structured and executed.

In shipbuilding—and yard operations in general—there are several possible building practices. These practices determine the sequence followed in performing certain stages of the production process, especially those related to outfitting. Some shipyards aim to erect the ship before the main outfitting work is initiated, while others focus on pre-outfitting the hull blocks before the blocks are joined to erect the ship. For yards that only perform outfitting on hulls built at other yards, the building practice is to perform outfitting work on a closed hull structure. These differences in building practices determine certain aspects of yard logistics.

Supply chain characteristics

Yard logistics is impacted to some extent by the supply to the yard. The supply chain characteristics factor describes aspects of the boundaries between suppliers and the yard.

The sub-factor supply network captures aspects such as offshoring of complete hulls or hull blocks, the supply of steel, and how the yard structures the supply of main equipment, such as engines. The way and type of supply to the yard impacts yard logistics when supplied materials are to be handled internally. For instance, yards that receive and handle ship blocks need high-capacity material handling equipment, such as cranes or multiwheelers, which are not required to the same extent at yards that receive complete hulls to be docked or placed quayside for further work.

The final sub-factor is vertical integration, which has been found to have an impact on productivity (Lamb & Hellesoy, 2002). Vertical integration with the ship owner, ship designer or main equipment suppliers can all impact yard logistics by enabling more seamless flows of both information and materials between the actors.

Applying the framework for yard mapping

The framework may be applied to describe yard environments. Moreover, as was done in paper 3, the framework can be applied to map and further compare different yard environments. In paper 3, three shipyards—one Norwegian (Ulstein Verft, UVE) and two South Korean (HHI Ulsan and STX Jinhae)—were mapped. Accordingly, the framework was used for a comparative analysis of different shipyards. This allowed for identifying and outlining the yards' main differences in the yard environment relevant to yard logistics and their implications. The mapping of the three yards is shown in Table 17.

Table 17: Framework application on three case shipyards.

Items	UVE	HHI Ulsan	STX Jinhae
Yard facilities	Pipe fabrication, outfitting, painting; quay (208 m), 1 graving dock.	Steel and pipe fabrication, assembly, outfitting, painting, pre-erection, erection; quay (7.4 km), 10 graving docks.	Steel and pipe fabrication, assembly, outfitting, painting; pre-erection, erection; quay (1.8 km), 2 graving docks.
Yard equipment	2 main traveling cranes (250 tons), 4 dockside and quayside cranes.	9 goliath cranes (max 1,600 tons), 33 transporters.	4 goliath cranes, 6 transporters.
Yard size	Around 75,000 m^2 and 300 shipyard workers.	Around 6,320,000 m^2 and 15,000 shipyard workers.	Around 1,000,000 m^2 and 1,000 shipyard workers.
Yard layout	L-shaped, with material flow directed towards hull in dock or at quay.	U-shaped from steel entry through fabrication, assembly, and erection to docks and quaysides.	
Automation level	Mostly manual operations, with some automation of fabrication.	High automation of steelwork and block assembly. Mostly manual operation for painting, outfitting, and ship erection.	High automation of steelwork and medium automation of block assembly. Mostly manual operation for painting, outfitting, and ship erection.
IT level	IT systems used for all business processes but with a low level of integration between systems.	IT systems used for all main business processes. High level of integration in the design phase. Low integration at yard.	
Vessel types produced	Offshore support vessels (PSV, OCV, SOV) and passenger ships (ROPAX, cruise).	Large size commercial carriers, offshore platform systems, and support vessels.	Tankers, gas carriers, cargo carrying vessels (container ships, bulk), and LNG bunkering.
Customization	Very high.	Very high.	Very high.
Total production volume	2 vessels per year.	70 vessels per year.	10 vessels per year.
Order size	Few—between 1 and 2.	Several—up to 20.	Several—up to 10.
Type and size of market	Mainly offshore, cruise, and passenger markets.	Maritime transport market and offshore market.	Maritime transport market.
Throughput time	20 months.	10 months.	12 months.
Main production process stages	Outfits complete hull structures in dry dock and at quayside.	Performs all production process stages at own shipyard (integrated yard).	Performs all production process stages at own shipyard (integrated yard).
Building practices	All outfitting work performed on closed hull.	Pre-outfitting of hull blocks.	Pre-outfitting of hull blocks.
Supply network	Hull production at a yard in Poland. Mostly local equipment suppliers.	Domestic and foreign suppliers of steel. Partly outsourced hull block construction. Two engine suppliers. Several domestic suppliers of other equipment.	
Vertical integration	Medium. Vertical integration with ship designer. Partnership with hull yard in Poland.	Very high. In-house ship design. Vertical integration with main equipment suppliers.	Low. Some in-house design.

Overall implications for yard logistics

Paper 3 highlights three main implications for logistics based on the mapped factors. The first implication is the yards' primary coordination focus. The mapping of the three yards in paper 3 shows the large difference in the number of ships built at each yard. Having many ships in construction at a single yard affects the yard logistics, as yard logistics activities must be coordinated across all the separate projects (ships). Paper 3 refers to this as inter-project coordination, that is, coordination between projects, with regard to yard logistics activities. Meanwhile, having only one ship in construction puts more focus on the single project (ship). Accordingly, the internal coordination of each project increases in significance compared to a situation where multiple ships are being constructed simultaneously. The coordination of yard logistics activities within a single project is referred to as intra-project coordination. Thus, the mapping and analysis reveal how the coordination focus is affected by characteristics of the yard environment.

Second, the factors and their items impact the scope of the yard logistics activities at the yards, as the yards differ in terms of the production process stages performed. Yards mainly performing outfitting operations can narrow their yard logistics focus towards those operations. On the other hand, the scope of yard logistics activities is greater for yards performing all of the production process stages themselves.

The third highlighted implication concerns the primary physical flows at the different yards. A yard's primary physical flow may be affected by the number of production process stages performed, production volume, product types produced, yard size, facilities, and equipment. For a yard performing outfitting operations, which is highly dependent on shipyard workers and involves one ship at a time, the primary physical flow may be the flow of workers to and from the dock or quay and on and off the ship being built. Meanwhile, for a larger shipyard, the most important physical flow is the flow of blocks and larger ship structures around the yard.

The mapping and logistics analysis illustrates how such a framework may be applied to investigate yard logistics. Accordingly, paper 3 contributes to enhancing the understanding of yard logistics and specifically investigates the factors affecting yard logistics.

4.2 Digitalized yard logistics

This section presents the results and findings related to the second research question: *How can digital technologies be applied to address current challenges and contribute to more efficient yard logistics?* The section is based on the research presented in papers 4, 5, and 6. In addition, sub-sections 4.2.4 and 4.2.5 provide additional contributions to the topic that are not found in the appended papers.

4.2.1 The fit of Industry 4.0 technologies to yard logistics

To understand how digital technologies can be applied to yard logistics, it is important to have a general understanding of how the applicability of digital technologies is affected by the manufacturing environment—and, more specifically, by the degree of repetitiveness of the manufacturing environment. To investigate this, a multiple-case study of four Norwegian manufacturing companies was conducted (case study I). The companies were selected to represent the range of different degrees of repetitiveness in their manufacturing environments. The paper set out to investigate the hypothesis that the applicability of Industry 4.0 technologies in manufacturing logistics (which in paper 4 is defined as a combination of the respective technology's ease of implementation and its potential positive impact) is dependent on companies' manufacturing environments. Accordingly, the cases were selected to represent different manufacturing environments.

The paper's research methodology had two main parts. The first involved qualitative mapping of each company's manufacturing environment, based on site visits, workshops and meetings with company representatives as well as existing documentation on the companies and their operations. From this mapping, the companies were described with regard to their manufacturing environments, and their respective degrees of repetitiveness were classified (see Table 18).

Table 18: Classification of case companies based on repetitiveness.

Variables	ETO company	MTO company	ATO company	MTS company
Automation level	Low	Low	Medium	High
Product structure complexity	High	High	Medium	Low
Level of customization	Customized	Customized	Semi-customized	Standard
Product variety	High	High	Medium	Low
Layout	Fixed position layout	Fixed position and cell layout	Functional layout	Product line layout
Material flow complexity	High	High	Medium	Low
Demand variation	High	High	Medium	Low
Relative degree of repetitiveness (from 1 to 4)	1	2	3	4

The second main part of the research contained a questionnaire on the applicability of Industry 4.0 technologies in manufacturing logistics. For each company, one questionnaire was answered collectively by a focus group. Each focus group consisted of representatives from the respective company as well as some researchers with insights regarding the company's operations.

The outputs from these two parts were then used to evaluate the applicability of a set of Industry 4.0 technologies for each of the case companies (Table 19).

Table 19: Evaluation of the applicability of Industry 4.0 technologies in four manufacturing companies.

Industry 4.0 technologies	ETO company	MTO company	ATO company	MTS company
Artificial intelligence	Low	Low	Medium	High
Big data analytics	Medium	Medium	High	High
Augmented and virtual reality	High	High	Medium	Medium
Sensors	Medium	Medium	High	High
Auto ID	Low	Medium	Medium	High
Networking technology	Low	Medium	High	High
Real-time control	Medium	Medium	High	High
Integration of IT systems	Medium	Medium	High	High
Cloud computing	Medium	Medium	Medium	Medium
Industrial robots	Medium	Medium	High	High
3D printing	High	High	Low	Low
Automatic guided vehicles	Low	Low	High	High

These results indicate that the applicability of Industry 4.0 technologies is affected by the degree of repetitiveness in the manufacturing environment. All the evaluated technologies were found to have a higher perceived applicability the more repetitive the manufacturing environment is, with the exception of AR, VR, and 3D printing. One of the cases was a shipbuilding company, and it was also found to have the least repetitive manufacturing environment, where Industry 4.0 technologies (in general) seemed least applicable. It must be noted that the investigations in this paper were conducted in 2016, when Industry 4.0 was still a novel concept. While the researchers and practitioners involved in the study all had some experience with Industry 4.0, it has advanced rapidly since. This issue must be considered in the discussion of the results. Nevertheless, these first investigations indicate that the overall applicability of Industry 4.0 technologies is lower in the least repetitive manufacturing environments.

The main takeaway from paper 4 is that the characteristics of the manufacturing environment that affect the repetitiveness will have implications on the applicability of Industry 4.0 in the context of manufacturing logistics. Hence, there is no "one size fits all" when it comes to Industry 4.0. A company-specific or at least industry-specific approach seems necessary to take advantage of the potential opportunities and benefits of Industry 4.0.

4.2.2 Outlining the potential impact of digitalization across entire supply chains in yard industries

While the main focus of this PhD study is to investigate yard logistics, and further, the applications of digital technologies in a yard logistics context, the potential of digitalization goes beyond this particular context. Decisions concerning specific areas such as yard logistics should not be made without considering the holistic perspective—in this case, the supply chain perspective. Therefore, paper 5 set out to outline, in general terms, some of the potential effects digitalization can have across entire supply chains in yard industries. The effects are evaluated based on the concept of sustainability and its three dimensions: economic, social, and environmental performance.

The paper is based on a case study of a Norwegian shipbuilding supply chain (case study III). It assesses the shipbuilding supply chain across five defined phases: design (including engineering), suppliers and logistics, manufacturing and assembly, product use, and product end life. For each phase, sustainability challenges are identified and described.

Next, the paper presents a review of digital solutions that have been suggested for shipbuilding or related ETO contexts. The review shows that a range of solutions have been proposed, and the paper further seeks to establish links between these solutions and the sustainability challenges they have the potential to address. Although many of the proposed solutions are still at a conceptual or pilot testing level, paper 5 explains how each of them is likely to have a positive effect on sustainability. Table 20 summarizes the sustainability challenges identified across the supply chain phases, the specific case study evidence they are based on, and the solutions identified for enhancing sustainability through Industry 4.0 technologies.

Table 20: Industry 4.0 solutions for addressing sustainability challenges in a shipbuilding supply chain.

Shipbuilding phases	Sustainability challenges	Case study evidence	Solutions for enhanced sustainability through Industry 4.0 technologies
Design	Impact on ship's environmental performance during ship operation	Ship design prioritizes operational cost-efficiency over improving environmental performance.	Optimization of ship design for increased energy efficiency through advanced (CAD) solutions and simulations.
	Inefficient and fragmented flow of information	Poor integration between design systems and those of other disciplines.	Effective sharing of knowledge and information between design, procurement, production, and project management through advanced and integrated information-sharing solutions.
Suppliers and logistics	Global sourcing (low proximity between actors)	Ship hulls are produced at a foreign shipyard.	Closer collaboration with suppliers through advanced information-sharing solutions.
	Complex and inefficient flow of information between actors	Several different IT systems used internally and between actors.	Increased information visibility and data availability through the application of RFID.
Manufacturing and assembly	Working conditions	High amount of manual labor, awkward and unsafe motions required by shipyard operators, and a lack of supporting tools.	Improved working conditions and workplace safety through operator support, such as wearables with sensors and AR technology.
	Productivity and cost-efficiency	Vast yard site with a poor overview of materials and time spent searching for and retrieving materials and information.	Increased productivity and efficiency of manufacturing logistics activities using IoT technologies and integrated IT systems to manage material and information flows at the shipyard.
Product use	Emissions and energy-efficiency	Shipbuilding company does not monitor ships in operation and the status of its sub-systems.	Utilizing Big Data and installing sensors in products that feed information to the manufacturer so it can be analyzed and optimized for future designs.
	After-sales services, maintenance, and repair	Spare parts production and stockkeeping disrupts normal production.	Additive manufacturing for the production of spare parts.
Product end life	Ship recycling	Unsatisfactory end-of-life handling of ships produced in the supply chain.	Establishment of a sustainable ship recycling industry, facilitated by cloud services and IoT, fostering job creation and reduced material and energy consumption.

The identified solutions and their expected effects with regard to sustainability highlight significant improvement potential for shipbuilding supply chains. This in turn illustrates the large positive implications of digitalization. Indeed, digital technologies are likely to offer solutions to existing problems and challenges.

Zooming back in on the yard logistics context, digital technologies may offer solutions to solve challenges related to productivity, cost-efficiency, and working conditions. However, it is still unclear how digital technologies should be applied. Therefore, the following section presents the features of digitalization that are necessary for yard logistics—a prerequisite for moving towards the next generation of yard logistics.

4.2.3 Required features of a digitalized yard logistics system

To address the importance of context in digitalization and the application of Industry 4.0 technologies, paper 6 aims to outline the main challenges related to yard logistics. In particular, the paper investigates a yard logistics environment through a single-case study (case study II). The underlying motivation is the idea that, for digitalization initiatives to be effective, they should address current challenges. They should be needs-based for the particular environment in which they are to be applied. Therefore, paper 6 set out to collect empirical data on the Norwegian shipyard Ulstein Verft AS (UVE).

The case study revealed four main yard logistics challenges:

- IT system integration and sharing of up-to-date information
- Localization of material, equipment, and tools
- Complex and information-demanding work for operators
- Manual material handling and irregular and disrupted flows

Following the identification of these main challenges, the literature on digitalization in ETO manufacturing was reviewed to identify possible applications of the Industry 4.0 technologies, listed in Table 4. The Industry 4.0 technologies and the identified applications can be found in paper 6.

The purpose of reviewing and identifying applications of Industry 4.0 technologies was to discover features of digitalization that could potentially address the context-specific challenges identified in the case study. For each yard logistics challenge, a corresponding required feature of digitalization was discovered:

- *Seamless, digitalized information* flow to secure better integration of internal IT systems and enable timely sharing of information based on the most up-to-date data.

- *Identification and interconnectivity*, allowing objects (materials, equipment, tools) to be identified and connected to each other and to the relevant IT systems, addressing the challenge of localizing materials, equipment, and tools throughout the yard.
- *Digitalized operator support* to efficiently and conveniently provide the on-site workforce with the required information.
- *Automated and autonomous material flow*, reducing the amount of manual material handling and enabling more efficient transportation of components, parts, assemblies, tools, equipment, and other objects in a yard.

Figure 9 shows the main identified challenges related to yard logistics and the corresponding required features of a digitalized yard logistics system.

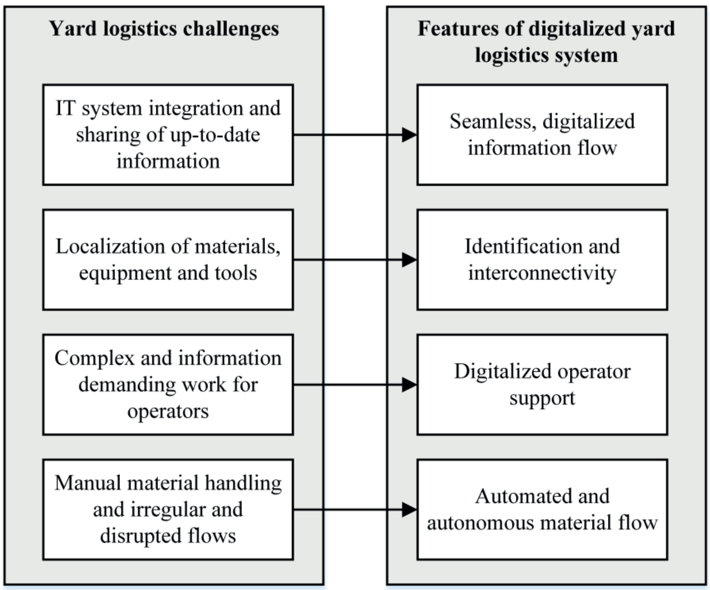

Figure 9: Yard logistics challenges and corresponding required features of a digitalized yard logistics system.

Having identified what is required from digital solutions to solve current yard logistics challenges, the next step towards next-generation yard logistics can be taken: conceptualizing digitalized yard logistics. This is further discussed in sub-section 4.2.5. First, a description of the current state of digitalization in yard logistics is provided.

4.2.4 Current state of digitalization in yard logistics

To outline the future steps in digitalization of yard logistics and to identify and develop the most feasible solutions, an overview of the current state of digitalization in yard logistics is necessary. As a part of case study V, digitalization was one of the areas mapped. Key aspects in the mapping were the yards' technology implementation, insights on the yards' strategic emphasis on digitalization, the yards' resources and initiatives with regard to digitalization, how IT systems are currently used to support yard logistics, and how integrated they are. Together, these aspects were combined to evaluate the current level of digitalization at each case yard. The results from the mapping and analysis of the current state of digitalization are shown in Table 21.

Table 21: Current state of digitalization in yard logistics at the case yards.

Case yard	Technology implementation	Digitalization strategy	Digitalization resources and initiatives	IT system use and integration of systems	*Digitalization level**
A	Wi-Fi throughout the yard, tablets for work management, AR-solutions have been tested in assembly, pilot projects on materials tracking.	Digitalization is a part of the company strategy. Pilot projects and proof of concept studies.	Dedicated resources and internal initiatives working on digitalization.	Several IT systems supporting yard logistics, but only partly integrated. Information made available for operators in digital format. Some digital connection to the yard floor.	***Medium***
B	Smartphone app for work management, development of digital twin in progress, investigating camera recognition for materials identification.	Digitalization is a part of the company strategy. Pilot projects and proof of concept studies.	Digitalization is a focus area, conducted mappings/studies on digitalization and how it can be applied in the company.	Several IT systems supporting yard logistics, but only partly integrated. Information made available for operators in digital format. Some digital connection to the yard floor.	***Medium***
C	Smartphone app for work management.	Digitalization is part of the company strategy. Pilot projects and proof of concept studies.	Digitalization is a focus area, conducted mappings/studies on digitalization and how it can be applied in the company.	Several IT systems supporting yard logistics, but only partly integrated. Information made available for operators in digital format. Some digital connection to the yard floor.	***Medium-***
E	No implemented digital technologies, informally introduced to AR/VR for the inspection of ships.	Digitalization is not part of the company strategy.	No specific resources for digitalization.	Only basic ERP functionality, with limited to no yard logistics support. Many administrative tasks are done manually, manual registration and writing of lists. No digital connection to the from yard floor.	***Very low***
G	Tablets for work management on a few previous projects	Digitalization not part of the company strategy.	No specific resources for digitalization.	Basic ERP functionality, IT system supporting basic procurement tasks. Manual administrative tasks. No digital connection to the yard floor.	***Low***
J	No implemented technologies.	No strategic emphasis on digitalization, although they recognize the need for digitalization.	No specific resources for digitalization, and they are involved in research project applications on the topic.	IT systems for specific applications, but not integrated to support yard logistics. Digital information printed on paper before distribution to operators. Many administrative tasks are performed manually, with manual registration and writing of lists—and manual checks of them. No digital connection to the yard floor.	***Very low***
M	No implemented technologies. Investigating the potential to use AR in research projects.	Digitalization is somewhat part of the company strategy.	No designated positions for digitalization. Some smaller digitalization initiatives and participation in research projects.	Partly integrated structure of IT systems, to some degree supporting yard logistics. Digital information printed on paper before distribution to operators. No digital connection to the yard floor.	***Medium-***
N	No particular technologies implemented.	No strategic emphasis on digitalization, although they recognize the need for digitalization.	No specific resources for digitalization.	IT systems for specific applications, but not integrated to support yard logistics. Digital information printed on paper before distribution to operators. Partly used item tagging system for identification of materials, however not automated and requires manual scanning of tags attached to the materials. No digital connection to the yard floor.	***Low***

*Digitalization level has been assessed using the following ordinal scale: Very low, low, medium-, medium, medium+, high, very high.

Based on the mapping of the current state of digitalization in yard logistics, it is evident that there is a long way to go to reach completely digitalized yard logistics. Although some yards belong to quite digitalized companies, in general, the realization of digital solutions on the yard logistics level is limited in the investigated case yards.

Only a few yards have already implemented technologies that are relevant for yard logistics. These primarily include digital devices for use by operators and supervisors as well as some small-scale implementations of AR/VR solutions. Although the use of these technologies is limited, the yards that have applied them characterize them as promising. Apart from the actual implementations, there are some tests and ongoing investigations of potential technologies at several of the yards.

The overall current state of digitalization in yard logistics is well illustrated by the use of IT systems for logistics at the yards in the study. Some yards do indeed have comprehensive, self-developed IT systems for logistics, which contain large amounts of data across the different areas of yard logistics. However, with only partial integration with other IT systems, there are still many manual administrative tasks related to extracting and transferring information between systems. Hence, the full benefits of such IT systems, where information flows seamlessly, have not yet been realized. Nevertheless, most of the yards in the study operate without any IT system for yard logistics. At these yards, information is extracted from the ERP system and carried over to yard logistics activities in analog formats.

The mapping of digitalization strategies concerns whether the digitalization is an explicit part of the strategy of the company operating the yard—and whether this is extended to yard logistics. With only four of the eight yards having digitalization as part of their company strategy, the mapping indicates that digitalization of yard logistics has not been a primary focus. Moreover, the lack of resources dedicated to working on digitalization initiatives seen in most of the yards may impede advancements.

In our selection of cases, the fabrication yards are the most digitalized with regards to yard logistics. However, it is likely that this is due to other factors than the yard types. One possible factor is the size of the companies operating the yard. Survey research has confirmed that large enterprises have a significantly higher level of digitalization than small and medium-sized enterprises (Buer et al., 2020), and the fabrication yards are operated by large enterprises. Another possible factor relates to the sectors the yards serve. Offshore construction typically has higher profit margins than shipbuilding and is, therefore, likely to have more resources available for company development initiatives such as digitalization efforts.

It is evident from the empirical data that there are significant barriers regarding implementation costs (and getting approval from top management) as well as difficulties in estimating the potential benefits of digitalization initiatives/implementations. For many yards, it is difficult to bear the investment costs and justify the potential investments. Some interviewees also pointed out the difficulty of finding solutions that are applicable in the harsh, physical environment of a yard—with large outdoor areas that are not protected from the weather, as well as metallic objects that can cause challenges for certain digital technologies such as localization systems. Another potential barrier is related to resistance to change. Although not evident from direct observations at the yards, some of the statements from the interviewees at several of the yards indicate that future implementations may cause reluctance among operators to apply new technologies in their daily work. However, this could be due to the immaturity or inapplicability of the technologies.

4.2.5 Towards a concept for digitalized yard logistics

In this last sub-section of the results chapter, knowledge developed in the previous parts of the thesis is integrated into a concept for digitalized yard logistics. The purpose of the concept is to propose—through descriptions and visualizations—ways of digitalizing yard logistics, so as to provide a solid "starting point" for moving towards next-generation yard logistics.

As described in section 3.2, the concept development was an extension of the case study analyses. In this way, the case studies formed the contextual foundation for the concept development, from which the yard logistics context could be understood. The concept development is further based on the digital technologies and solutions that were identified through literature reviews for papers 5 and 6. The concept is based on technologies that are available today and aimed towards realistic implementations of digital technologies in an industrial context, i.e., what it could look like in the foreseeable future). Paper 6 identified four required features of a digitalized yard logistics system, and in the concept development process these are transformed to the four elements of the concept for digitalized yard logistics. The concept and its four elements are shown in Figure 10 and described in detail in the following paragraphs.

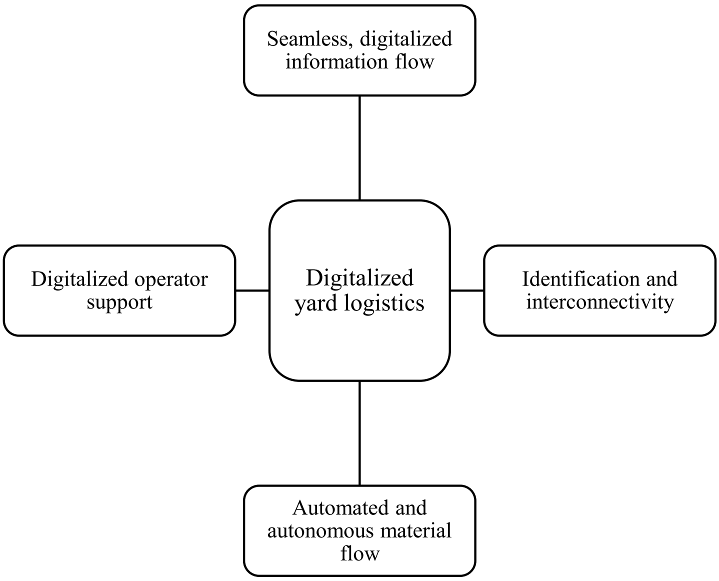

Figure 10: Elements of the concept for digitalized yard logistics.

Seamless, digitalized information flow

Efficient yard logistics relies on efficient distribution of the information that is required to execute yard logistics activities and make decisions. Especially, the close interaction between non-physical processes, such as engineering and project management, and production requires integrated IT systems for the efficient control and execution of the yard logistics activities. There is a need for a seamless, digitalized information flow, where all subsystems are integrated. Information should flow from higher-level IT systems to the production floor whenever needed, providing access to real-time information. The general purpose of such seamless, digitalized information flow is to make the relevant information available for the executing actors.

Key aspects of seamless, digitalized information flow in yard logistics include:

- The supervisors receive up-to-date, digitalized information from higher-level systems, such as ERP and project management systems, regarding the next work packages to complete, operator availability, material status, and resource availability (facilities, production halls/areas, transportation resources) required for the distribution of work packages.
- Assigning a work package (by a supervisor in a control system) could potentially activate the required actions (the information is sent) to pick and bring the material to

the place of use (e.g., booking transportation and giving information to the transport equipment that will perform the transportation) and activate the provision of information (work package description) to the operators the work package was assigned to.

- The transportation operators (or automated and autonomous transportation equipment), upon being assigned to an internal transportation job, receive information regarding the correct items to pick, where to pick them from, and where to deliver them.
- The production operators, upon being assigned to a work package, receive the information required to execute the job, such as drawings, work instructions, and about which items (both material and equipment) are to be used and their locations in the yard.
- Warehouse operators receive the required information upon receipt of incoming materials to the yard and upon receiving internal material requisitions for internal supplies.
- Progress reports from operations are automatically and instantly sent in a digital format to the relevant parts of the yard organization.

Identification and interconnectivity

It is challenging to gain an overview of all the materials, equipment, and tools needed to perform yard logistics activities. IoT, with objects equipped with sensors and actuators to enable storing and sharing of information, have the potential to mitigate these challenges by providing identification and interconnectivity. Identifying and interconnecting objects in a facility would enable a highly integrated way of managing operations. The general purpose of identification and interconnectivity is to provide a complete overview of the yard's materials, equipment, and tools. We consider two possible approaches to real-time location of objects:

- Physical object tagging of:
    - Materials—transmitting information about their location, status, etc. This information should then be available for the relevant logistics systems (e.g., for picking the correct items from storage, finding them without having to search).
    - Transportation resources—enabling the networking of all transportation resources, potentially improving the process of selecting resources for different transportation jobs (e.g., booking of an available and close resource for a transportation job).

    - Other equipment used by operators.
- Identification of objects through vision/recognition technology
    - Cameras mounted on transportation equipment, building structures, operators' helmets, drones, or other suitable places, to scan objects in order to identify them, update location, view status, etc.
    - The information acquired is transmitted to relevant logistics systems or used directly by the transportation equipment, operator, or drone for its current task (e.g., to pick the object it is looking for).

Independent of the technical solution, the ability to identify and interconnect objects in the yard will present great opportunities with regard to the management of the objects.

Digitalized operator support

In yard logistics, it is critical for the operators to receive timely and correct information about the tasks to be performed, such as, drawings and work instructions. Digitalized yard logistics should therefore include digitalized operator support. Digital technologies should be utilized to provide enhanced support, ensuring rapid and easy access to required and up-to-date information.

Key aspects of digitalized operator support include:

- Work package descriptions available electronically on handheld devices, such as tablets or smartphones.
- AR or VR solutions to support various tasks, including:
    - Warehouse operations such as picking, where AR-based information can provide enhanced information on where to find the correct item in the warehouse.
    - Outfitting jobs, where AR solutions can be used to visualize the operators' tasks. For instance, the specific item to be installed on a ship can be projected—through AR-glasses—showing the operator where it is to be installed.
- Digitalized solutions for operators and supervisors to report progress. This should make the important activity of progress reporting as convenient as possible.

Automated and autonomous material flow

With the comprehensive material flow at yards, great potential lies in making material flow more efficiently. In yard logistics, digital technologies can bring autonomy and automation to the physical flow of materials. Components, parts, assemblies, tools, equipment, and other objects could then be transported more efficiently and with less human intervention.

Key aspects of automated and autonomous material flow in yard logistics include:

- AGVs, AMRs, and collaborative robots operating in warehouses
- Automated and possibly autonomous conveyors, cranes, and vehicles (self-elevating transporters, multiwheelers, etc.) for transporting heavy or high-volume materials around the yard
- AMRs (vehicles or drones) for transporting light, low-volume materials around the yard
- Automatic storage systems, such as Pater Noster material handling systems

Together, these four elements form a holistic concept for digitalized yard logistics. Figure 11 shows ten features the concept can bring to yard logistics, indicated by the numbers 1 to 10:

1) Digital product information from design and engineering to supervisors and operators.
2) Cloud-based information management for yard logistics information, including product information from design and engineering, progress information from production, inventory information from warehouse, work package information, etc.
3) Supervisors equipped with digital devices with information relevant for work management.
4) Digital assignment of work packages to operators, along with work package descriptions and product information made available for operators on digital devices.
5) Interconnection of transportation equipment, receiving information on new jobs, such as, when and where to pick up which materials and where to deliver them.
6) Identification and location of objects through physical object tagging or vision technology.
7) Items in warehouses identifiable through technology and connected to work packages based on availability and needs.
8) Autonomous material handling in warehouses and other storage areas.
9) Operators performing outfitting operations equipped with AR devices that provide support during outfitting.
10) Yard equipment interconnected and digitally assigned to jobs, with digital communication of status.

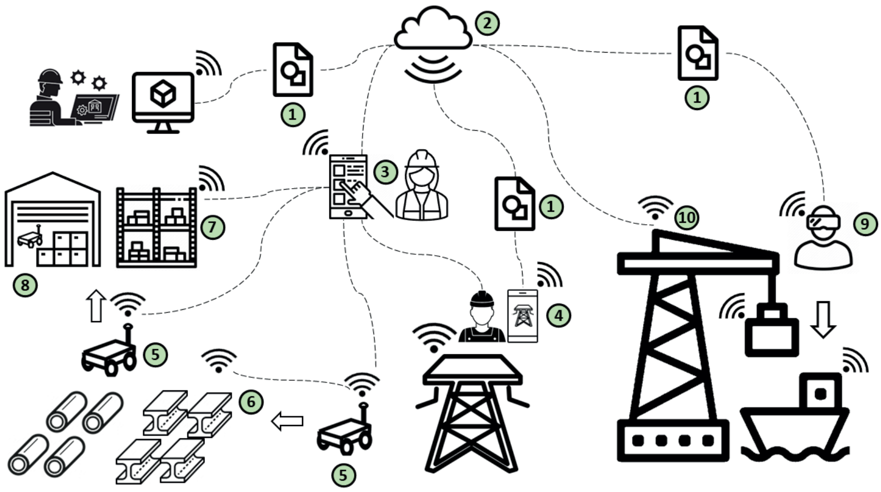

Figure 11: Visualization of the ten features of the concept for digitalized yard logistic.

The concept has been developed on the basis of technologies that are available today, albeit not currently commonplace at yards. Accordingly, there are several technology requirements that are necessary for the concept to be realized, which include the following:

- AR devices. There are several types of AR devices available today that may suit a yard logistics context. A physical device, in the form of a smartphone, tablet, headset or glasses, equipped with the required hardware and software to run AR applications is necessary.
- Identification technology system, either based on physical object tagging, for example a RFID system, or based on vision/recognition technology. This requires both hardware and software.
- Autonomous vehicles and automation technology for autonomous and automated material handling.
- Networking technology to transmit information wirelessly between systems, objects, etc.
- Software for logistics control, including the control logic.

For the successful realization of such a heavily technology-based concept, the human aspect of yard operations must be considered and addressed. Certain parts of the concept build on operators' adoption of new technologies, such as wearables and other digital devices, in their daily tasks. Accordingly, this may require changes in the way the people involved in yard logistics work. For the described concept, adaptation is needed with regard to the use of AR devices, such as glasses and headsets, interacting with digital interfaces (e.g., smartphones and tablets), and becoming accustomed to autonomous vehicles operating in the yard.

Another important issue for the realization of such a concept relates to the investment requirements. The mapping of the current state of digitalization indicates that there are potential barriers related to the investment costs. With the high uncertainty in the yards' current situations, it is associated with great risk to make any investments if they cannot be covered through current projects. Moreover, the novelty of a technology may make it difficult to estimate the potential benefits.

Although the economic benefits may not be easily quantified, it is possible to qualitatively discuss the potential effects of digitalization on yard logistics performance. Table 22 connects some potential effects of the four concept elements with the performance measures for yard logistics presented in sub-section 4.1.6 (Table 15).

Table 22: Potential effects of digitalization on yard logistics performance.

Performance measures	**Seamless, digitalized information flow**	**Identification and interconnectivity**	**Digitalized operator support**	**Automated and autonomous material flow**
Requisition lead time: Lead time to requisition work package material from the warehouse		More rapid location of the materials to be picked	Increased operator efficiency, e.g., through solutions to assist in material picking, reducing picking time	More efficient warehouse operations with automated solutions
Production time lost: Production time lost due to materials availability		Less time spent locating materials due to enhanced localization through networking of objects		
Internal delivery precision: Warehouse deliveries received on time at the place of use	Digital information flow enhances internal order processing involving production and warehouse			More efficient internal transportation through automated transportation
Transport efficiency: Number of transports per unit		Enhanced transport efficiency through better overview of items, facilities, and equipment.		
Put away cycle time: Time elapsed after incoming materials are delivered to the yard until they are put away in the warehouse	Reduced put away cycle times for incoming materials due to rapidly, digitally available information on materials and their destined warehouse locations			Reduced put away cycle time due to automated material handling solutions in warehouse
Order picking cycle time: Average order picking cycle time for internal orders placed to the warehouse			Increased productivity of operators, e.g., though solutions to assist in material picking	Reduced order picking cycle times due to automated warehouse solutions
On-time work package completion: Percentage of work packages completed within due date			Increased productivity of operators, e.g., through digitally available up-to-date work package descriptions	
Information quality: Amount of perfect work package descriptions	Improved information quality due to enhanced, digital information exchange			
Operator efficiency/productivity: Operators' non-value-adding time.		Better overview for operators, reducing the unnecessary time spent walking and searching for items		

5 Discussion

In this chapter, the results presented in Chapter 4 are discussed. The chapter reflects on the stated objective of the research study: To develop knowledge on yard logistics needed to improve yard logistics performance and identify how digitalization can support logistics improvement. More specifically, for each of the two research questions, the main findings are summarized and then explained and discussed in relation to the existing literature.

5.1 The conceptualization of yard logistics

The first research question was formulated to identify the constituents, characteristics, and challenges of yard logistics, with the aim to discover, develop, and structure knowledge on yard logistics. To answer this research question, we reviewed the existing literature and analyzed empirical data collected through two multiple-case studies. This was then used to define and characterize yard logistics, including describing its constituents and identifying its challenges.

The main findings related to RQ1 can be summarized as follows:

- Definition and characterization of yard logistics, including the constituents of yard logistics, according to a typology of yard operations (paper 1)
- Identification of yard logistics challenges (paper 1)
- Performance measurement system for yard logistics (paper 2)
- Identification of factors affecting yard logistics (paper 3)

This research study is differentiated from the existing literature by its holistic perspective on yard logistics, that is, a logistics perspective on yard operations. Previous research has primarily targeted specific yards, such as integrated shipyards (Jeong et al., 2018b), outfitting yards (Wei, 2012), offshore construction yards (Gi Back et al., 2017), and service yards (Sinha et al., 2005). Moreover, existing works often focus on specific yard logistics problems within those contexts. For instance, in Jeong et al. (2018b) the yard logistics focus is on the transportation of ship blocks. In contrast, this thesis takes a wider perspective on yard logistics, where the transportation of ship blocks is considered as one of many other aspects. As another example, Bruce (2021) describes an ideal layout for a modern, large, integrated shipyard, detailing the placement of facilities and relevant production process stages for such a yard, whereas this thesis focuses on more generic considerations of a yard’s layout across different yard types. Similar differences apply to the existing coverage of the shipbuilding process. For example, Kanerva et al. (2002) examine the shipbuilding process in detail. Our research extends the knowledge on yard logistics by bridging the various sub-contexts, thereby adding structure and a holistic perspective to yard logistics.

Furthermore, the focus in existing research is often on single logistics problems at single yards. While investigations of multiple yards have been carried out (see e.g., Semini et al. (2018) and Pires Jr et al. (2009)), they have not focused on logistics. The collection of empirical data from several yards allows for more comprehensive descriptions of the constituents. The broader perspective on yard logistics adopted in this research and the collection of empirical data from several yards thus add to the existing literature in that regard.

Our identification and structuring of yard logistics constituents resembles the shipyard production system and its six elements described by Lee et al. (2014). Nevertheless, there are certain differences that illustrate how such a specific system for shipbuilding production management differs from the more generic yard logistics considerations in this thesis. One main difference is the scope of shipbuilding versus yard operations. Furthermore, the shipyard production system description by Lee et al. (2014) is more concerned with tactical aspects, whereas this thesis focuses on operational logistics.

As reported by Cannas and Gosling (2021), the ETO literature has expanded in the last decade, with additional sectors emerging. However, it is still dominated by the construction and machinery sectors. This research adds additional insights to a part of ETO that still has potential for further exploration. Additionally, while it is positioned within the ETO literature, this thesis provides a more nuanced view on the structure and control of a specific ETO logistics system—the yard logistics system—including its main constituents, key characteristics, and challenges. Accordingly, the thesis extends the ETO literature to the yard logistics context.

Typologies are commonly used to structure findings within operations and supply chain management in general. However, there is a scarcity of comparative studies and cross-case analyses of yards in the literature. Yards, or products produced at yards, are not included in previous classifications based on empirical data within the ETO context (Amaro et al., 1999; Hicks et al., 2001; Shenhar, 1998; Willner et al., 2016). Therefore, the knowledge on yard logistics provided in this thesis, particularly the typology of yard operations, adds to the previously mentioned works.

There are several other approaches that could have been followed for the development of a typology within yard logistics, for example, by distinguishing types based on yard size or the products and services delivered rather than by yard operation types. The purpose of the typology in paper 1 was to enable the distinction and comparison of yard logistics-related aspects—or the constituents of yard logistics. For this purpose, yard operation types were found to be the most relevant aspect, as the purpose of yard logistics is to facilitate efficient operations. It is possible that a distinction of yards based on yard size or products/services would yield different classifications of yards than presented in this research, and such distinctions could have been used to describe yard logistics, including differences and similarities based on yard size, products or services, or other aspects of investigation. Nevertheless, we are confident that the selected approach was best suited to fulfill the purpose of the research.

Paper 3 investigated the context dependence of yard logistics by identifying and analyzing the factors affecting yard logistics. Its main result is a framework for mapping and describing a yard environment, based on the factors that can affect yard logistics. Although the framework was based on the shipbuilding literature and the cases the framework was applied to map were shipyards (see Table 17), there are no indications that the framework would not be applicable to other yards as well.

Yard facilities, areas, and equipment as well as yard layout are all listed as factors affecting yard logistics as well as logistics constituents. One could argue that they should be one or the other. However, there are arguments for including them in both categories. For existing yards, the yard layout is largely fixed, and it can be considered unrealistic to change it without major changes to the yard. The existing layout, therefore, has implications on, for example, how materials can be physically moved around. Thus, it can be considered a factor that affects yard logistics. The same applies to the facilities, equipment, and areas at the yard, which can also be considered fixed. At the same time, they are all structural elements that must be part of a description of yard logistics, and they are therefore listed both as factors affecting yard logistics as well as yard logistics constituents.

The identification of factors affecting yard logistics and the analysis of their impact on yard logistics are consistent with earlier studies related to context dependency in operations management (Buer et al., 2021; Congden, 2005; Fernandes & Godinho Filho, 2011; Jonsson &

Mattsson, 2003; Sousa & Voss, 2001). Yard logistics seem to be dependent on contextual factors related to products, markets, and process.

Performance measurement in yard logistics, investigated in paper 2, has some similarities to performance measurement in other ETO sectors. The examination of performance measurement in yard logistics illustrates the applicability of performance indicators from similar industries/sectors within ETO, such as aerospace (Telles et al., 2020) and construction (Kusrini et al., 2018). On the other hand, the process of designing a performance measurement system for yard logistics highlights the need for adaptation to the specific context. For instance, certain measures suggested by Sjøbakk et al. (2015), Telles et al. (2020), and Kusrini et al. (2018) were only found to be applicable after adaptation to the yard logistics context. Accordingly, while performance measurement in different ETO contexts appears to be comparable, the specific systems and measures for each context require tailored measures.

5.2 How digital technologies can be applied to contribute to more efficient yard logistics

The second research question was formulated to identify how digital technologies can address the challenges in yard logistics and how they can contribute to more efficient yard logistics. To address this question, we complemented the knowledge developed from research question 1 with a review of the literature on digitalization and empirical data from both single-case and multiple-case studies. Furthermore, the existing knowledge base and empirical data served as inputs in a process to develop a concept for digitalized yard logistics.

The main findings related to RQ2 can be summarized as follows:

- Insights into the context-dependency of the applicability of Industry 4.0 technologies (paper 4)
- An outline of the potential impact of digitalization across entire supply chains in yard industries (paper 5)
- Identification of the required features of a digitalized yard logistics system (paper 6)
- Overview of the current state of digitalization in yard logistics
- Proposed a concept for digitalized yard logistics, and linked the elements of the concept with yard logistics performance improvements

Paper 4 investigated the context dependency of digital technologies. While it has been previously shown that the degree of repetitiveness is a critical factor in the choice of a PPC system (MacCarthy & Fernandes, 2000) and that the choice of planning methods is dependent on the manufacturing environment (Jonsson & Mattsson, 2003), the results of paper 4 indicate that the degree of repetitiveness in the manufacturing environment also affects the applicability of Industry 4.0 technologies. However, in contrast to the linear relationship between the applicability of Industry 4.0 technologies and repetitiveness, as paper 4 suggests, the findings of Buer et al. (2020) indicate that the relationship has an inverted U-shape, based on lower implementation levels at each end of the repetitiveness scale, found in their survey research. One possible explanation for the results of paper 4 is that Industry 4.0 in its early years could have been interpreted as a vision directed towards mass production industries. A seemingly typical perception is that things are “not applicable” when product and process complexity is high and repetitiveness is low, as the manufacturing situation is seen as “too unique” to fit a standardized technological solution developed for mass production industries. While application in non-repetitive production may be more difficult than in more streamlined production, it is certainly not impossible. However, the implementation of new technologies may have been hampered by such a perception. Further possible explanations for the results are provided in paper 4.

With the research presented in paper 6, this thesis takes a needs-based approach to digitalization rather than an approach that is based technological opportunities. Several existing works have investigated possible applications of technology in relevant contexts, especially within shipbuilding, as reviewed and discussed in paper 5. This thesis has addressed the gap in research efforts to link current challenges to technology-independent features of digitalization.

It seems evident, both from existing research and the research in this study, that there is a long way to go for yards to reach an Industry 4.0 level of yard logistics. Moreover, the results indicate that yards are lagging behind with regard to the digitalization of yard logistics. Yard operations are still characterized by manual work—both physical and administrative. This is consistent with what has been reported in the shipbuilding industry (Sanchez-Gonzalez et al., 2019; Stanić et al., 2018) and the need for further research efforts on digitalization that has been emphasized for ETO in general (Zennaro et al., 2019). Conversely, the survey research of Buer et al. (2020) did not find statistically significant evidence of a lower level of implementation of digital technologies in non-repetitive manufacturing environments compared to other manufacturing environments. However, the unit of analysis in that study was companies. The experience from the yard visits for the case studies of this thesis is that the companies operating the yards may indeed be quite digitalized in the general sense. For instance, the development of the ships produced at some of the investigated yards requires highly advanced technology. It is reasonable to assume that these companies (not the yards) would score well on an assessment of their level of digitalization. In this research, however, the focus has been on yard logistics, and in that area the level of digitalization seems lower than in other contexts.

Furthermore, it seems that company size is significant for the level of digitalization of yard logistics, as it has been found to be for the manufacturing industry in general (Buer et al., 2020). The mapping of the current state of digitalization in yard logistics shows that the yards operated by the largest companies are not necessarily more digitalized, but they may have more resources dedicated to digitalization as well as more defined digitalization strategies. Additionally, these yards have a greater capability to run development and pilot projects to investigate the applicability of new digital technologies.

Several of the typical barriers to digitalization (Da Silva et al., 2020; Raj et al., 2019) were evident at the yards studied in this research. In particular, financial barriers, such as a lack of clarity regarding the economic benefits and high investment costs of digitalization, were commonly noted by interviewees in case study V. Even the yards of the largest companies expressed challenges related to these two barriers. Typical barriers aside, technological barriers related to the applicability of technologies in the harsh, physical yard environment may be a peculiarity in the yard context as such barriers are not mentioned in Da Silva et al. (2020) or Raj et al. (2019).

Resistance to change and ineffective change management are potential barriers that become more prevalent as implementation progresses. These barriers are not as relevant today, as there have been few major changes in terms of digitalization at the investigated yards. However, the yards appear to be quite conventional when it comes to modernization and implementation of new technologies, and so it is possible that such barriers related to change may manifest in the future. Nevertheless, if the barriers can be overcome, the research indicates that several of the expected benefits of Industry 4.0 (Dalenogare et al., 2018) are achievable in yard logistics. The finding of Winkelhaus and Grosse (2019) that Industry 4.0 can have a great influence on internal logistics seems to apply to the yard logistics context as well.

The development of a concept for digitalized yard logistics is an effort to extend the general conceptualizations of digitalization (Dalenogare et al., 2018; Fatorachian & Kazemi, 2020; Frank et al., 2019) to the yard logistics context. The existing literature includes some partly related conceptual descriptions. For example, Ang et al. (2017) present a general framework for digitalized ship design and engineering, production, and operation, focusing on the general impacts digital technologies can have on energy efficiency throughout the life cycle of ships. With its wide scope, the concept is quite general. Stanić et al. (2018) describe “shipbuilding 4.0”—a general concept regarding the digitalization of shipbuilding, including shipyards, shipowner, suppliers, and other actors in the shipbuilding supply chain. Furthermore, Woo and Oh (2018) describe “digital shipbuilding”—a computer-based production management concept for modeling and simulating stages of the shipbuilding process. Accordingly, the concept described in sub-section 4.2.5 of this thesis stands out because it addresses the digitalization of yard logistics—a narrower scope than existing shipbuilding concepts, and a wider scope than concepts focusing on modeling and simulating shipbuilding. By building on the technological solutions that have been explored and described in the existing literature, a holistic concept has been developed in which these individual technologies are interconnected and work together.

The potential impacts of digitalization on yard logistics, described in sub-section 4.2.4, are in line with the general impacts of digitalization on the area of internal logistics described by Zheng et al. (2021), which include material identification and tracking, automation of internal transportation, order picking management, and AR for operator support in warehouse operations. Further, using the specific performance measures presented in paper 2, the potential impacts of digitalization on yard logistics can be detailed, as shown in Table 22. Considering the lack of clarity regarding the economic benefits of digital technologies, which is a prominent barrier for yards, even more specific and precise estimates of the potential benefits seem necessary to take the next steps towards the digitalization of yard logistics. Thus, this a key task for further research.

6 Conclusions

This chapter concludes the thesis. It includes a short summary of the research and provides some concluding remarks before describing its theoretical contributions and the implications of the results for practice. Finally, the chapter addresses the research limitations and suggests further research.

The objective of this thesis was *to develop knowledge on yard logistics to improve yard logistics performance and identify how digitalization can support this improvement*. To achieve this, the following two research questions was posed: *How can yard logistics be conceptualized?* and *How can digital technologies be applied to contribute to more efficient yard logistics?* The research utilizes case research as the main research method to qualitatively examine topics related to yard logistics and digitalization. As a result, the thesis provides new, structured knowledge on yard logistics and outlines how yard logistics can be digitalized. The main outcomes include the following:

- A definition and characterization of yard logistics, including the constituents of yard logistics, according to a typology of yard operations
- Identification of yard logistics challenges
- Performance measurement system for yard logistics
- Identification of factors affecting yard logistics
- Insights into the context-dependency of the applicability of Industry 4.0 technologies
- An outline of the potential impact of digitalization across entire supply chains in yard industries
- Identification of the required features of a digitalized yard logistics system
- An overview of the current state of digitalization in yard logistics
- A description and visualization of a concept for digitalized yard logistics incorporating digital technologies

The results of this thesis advance the field of yard logistics, supporting the development of solutions that could increase the cost-efficiency of yard logistics. It provides a foundation for both research and practice to further develop the field as well as to embrace the opportunities offered by digital technologies within Industry 4.0.

6.1 Contributions to theory

The thesis provides several contributions to theory. Table 23 lists the main contributions and indicates the respective papers in which the contributions are disseminated. Each contribution is further addressed in the following paragraphs.

Table 23: Overview of the main contributions to theory.

Main contributions to theory	**Paper 1**	**2**	**3**	**4**	**5**	**6**
Definition and characterization of yard logistics	**X**					
Typology of yard operations	**X**					
Contextualization of performance measurement to yard logistics		**X**				
Identification of factors affecting yard logistics			**X**			
Identification of dependencies between Industry 4.0 applicability and manufacturing environment				**X**		
Establishment of a link between yard logistics challenges and digitalization					**X**	**X**

The first main contribution of the thesis is the definition and characterization of yard logistics. This extends the knowledge and understanding of the field of internal logistics to a context in which such fundamental descriptions have been lacking. This is considered crucial for establishing a solid, common understanding of the concept and field of yard logistics. In particular, it could provide support for future research.

Second, building on the definition and characterization of yard logistics, the thesis has provided a typology of yard operations. This typology differentiates between the primary yard operation types, enabling a highlighting of the logistics differences and commonalities of yards engaged in different types of operations. With this typology and its application, the thesis provides structure to the field of yard logistics.

Third, through paper 2, the thesis contextualizes performance measurement to yard logistics. Accordingly, it contributes to expanding the field of performance measurement to the yard logistics context by proposing a performance measurement system that is aligned with the specific characteristics of yard logistics.

The fourth theoretical contribution relates to the contextual factors of yard logistics, which are presented in a framework for mapping the factors affecting yard logistics. This framework addresses the relationship between yard logistics and the factors affecting it, further enhancing the knowledge and understanding of yard logistics.

Paper 4 investigates the relationship between the applicability of Industry 4.0 technologies and manufacturing environments. It links the applicability of Industry 4.0 technologies to manufacturing environment characteristics, suggesting contingency in this relationship. Accordingly, the thesis contributes to contingency research in operations management and can help us understand which technologies are applicable in which contexts.

Finally, papers 5 and 6 contextualize digitalization to yard logistics. They link yard logistics challenges—identified though empirical data—to features of digitalization and specific digital solutions. Thus, the thesis contributes to expanding the field of digitalization of manufacturing and logistics to the context of yard logistics and yard industries. This enhances the general understanding and knowledge of the potential impacts of digitalization and widens the solution space for solving yard logistics challenges.

6.2 Implications for practice

A key premise in this research study is that enhanced knowledge on yard logistics can be used to develop solutions that can improve yard logistics performance. The definition and description of yard logistics in this thesis, including the characteristics and challenges of yard logistics, can pave the way for practitioners to develop appropriate logistics solutions that fit the specific logistics context of a yard. Together with the typology of yard operations presented in this thesis, yards can use this information to compare themselves against other yards with regard to their yard logistics. Accordingly, practitioners can study the commonalities and differences between yards and possibly deepen their understanding of their own yard logistics system while learning from the systems of others. This understanding is necessary for decision-makers to select and implement appropriate improvement strategies, which can have a significant impact on yard logistics performance.

This thesis also proposes a set of performance measures for yard logistics. In this way, the thesis provides tangible measures that could improve the practical applicability of performance measurement for yards. The proposed measures, and the insights on how the yard logistics context impacts performance measurement, may be used by practitioners as a guide in their own development of yard-specific performance measurement systems.

The thesis provides several important insights regarding the digitalization of yard logistics. First, it emphasizes the need for context-specific approaches to digitalization. This should urge practitioners to be fully aware of the characteristics of their respective yard logistics system before implementing digital technologies. Second, it identifies features of digitalization connected to specific yard logistics challenges. This further supports yards in identifying digital solutions to existing logistics challenges that can lead to improvements in yard logistics performance. This should serve as a baseline for developing digitalized yard logistics systems that address current challenges. With this link established, practitioners can prioritize digitalization initiatives with the intention to solve targeted challenges.

Furthermore, the thesis identifies and reviews a range of available digital technologies that can be applied in yard logistics specifically, as well as across entire supply chains in yard industries. This can provide practitioners with an overview of the available technologies and their potential applicability, which can serve as a basis for their selection and implementation of appropriate technologies for their yard logistics systems.

Additionally, the thesis provides an overview of the current state of digitalization in yard logistics based on empirical investigations. This information could be used to better understand a yard's advancements with regard to digitalization. With more empirical data, such an overview of the current state can be used as a benchmarking tool to evaluate the digitalization level of yard logistics.

As a final contribution to practice related to yard logistics digitalization, the thesis proposes a concept for digitalized yard logistics. The concept builds on the link between yard logistics challenges and features of digitalization and conceptualizes how such features can be realized in yard logistics. Such a concept may serve as a starting point for more advanced and specific developments as well as possible realizations of digitalized yard logistics systems.

Combined, these implications for practice can form a 6-step model towards next-generation yard logistics, shown in Table 24.

Table 24: 6-step model towards next-generation yard logistics.

Steps towards next-generation yard logistics	Research outcomes supporting the steps
1. Map and understand the particular yard logistics system and yard logistics context	Definition, characterization, and constituents of yard logistics (Sections 4.1.1-4.1.4) Factors affecting yard logistics (Section 4.1.7)
2. Identify and describe current yard logistics challenges	Yard logistics challenges (Section 4.1.5)
3. Identify performance goals and possible measures	Performance measurement system for yard logistics (Section 4.1.6)
4. Identify the relevant features of digitalization	Required features of a digitalized yard logistics system (Section 4.2.3)
5. Assess the possible digital technologies, their potential impact, and compare the yard with others	Potential impact of digitalization across entire supply chains in yard industries (Section 4.2.2) Overview of the current state of digitalization in yard logistics (Section 4.2.4)
6. Define a yard-specific concept for digitalization	Concept for digitalized yard logistics (Section 4.2.5)

6.3 Research limitations

The research in this thesis has some limitations. Although the specific limitations for each of the research studies that are part of this thesis are addressed in the respective papers, we provide some considerations with regard to the limitations of the thesis in general in the following paragraphs.

As has been touched upon in Chapter 3, the choice of case research as the main research method has some limitations due to the weaknesses of case research. For the multiple-case studies, the level of detail of the data obtained from each case in those studies is lower than the level of detail that could have been achieved with a single-case study design. Although this research design was chosen to best answer the research questions, we acknowledge this limitation. At the same time, given the choice of conducting multiple-case studies, the total number of cases can be considered a limitation. A higher number of cases could have allowed statistical generalizability of the results. However, that was not the goal of this research, and we are confident that the chosen research design was best suited to the purpose of the research.

Due to its qualitative approach, the research in this study has limitations related to the lack of quantitative data. Accordingly, the analyzed data cannot be measured. Nevertheless, the deliberate choice of a qualitative approach was made to gain insights that would not have been possible with a purely quantitative approach.

The research in this thesis focused on internal logistics at yards due to its high impact on costs and productivity, and the relevance and importance of yard logistics was acknowledged by interviewees in the case studies. Nevertheless, other aspects related to yard operations and digitalization that may be relevant for yards were considered to be outside the scope of this research. Accordingly, the research scope may have caused some limitations by neglecting other aspects with potential impacts on costs and productivity.

The research in this thesis targeted a specific aspect of ETO manufacturing: yard operations. While some of the findings may be transferable to other ETO sectors, such as construction, this has not been specifically investigated as part of this research, and thus the generalizability to other ETO contexts is limited. However, this provides an opportunity for further work.

Although the research has been aimed at developing generic knowledge on yard logistics, the results are to some extent limited by the specific focus on the challenges of yards in high-cost countries, and the fact that most of the cases involved in the research are Norwegian yards. Especially, the findings from case study V—the multiple-case study of eight Norwegian yards as the foundation for the definition and characterization of yard logistics, including yard logistics constituents, yard operation types, and yard logistics challenges—may not be directly applicable to yard logistics at yards in low factor cost countries. On the other hand, the findings should be applicable to yard logistics in comparable countries with regards to factor costs, especially in Western Europe.

Finally, the thesis has limitations related to the limited discussions, workshops, and feedback on the proposed concept for digitalized yard logistics. Although the concept development process utilized input from practitioners, the concept has not been validated or tested in the form in which it is presented in this thesis.

6.4 Further research

The research conducted in this thesis, including its findings and limitations, reveals both needs and possibilities for further research to advance the knowledge on yard logistics and digitalization.

It has been indicated, both in this research as well as in the existing literature (Buer et al., 2020; Zennaro et al., 2019), that there are challenges related to digitalization in non-repetitive production, such as yard operations. A general suggestion for further research would be to continue to address these two domains jointly—digitalization and non-repetitive production—

specifically investigating the contextual factors, such as product, market, and process characteristics of those types of production, and their impact on digitalization.

Furthermore, we see potential in extending the yard operations typology. With more empirical data on different yards, the typology could be extended and enable descriptions of additional yard types, such as the integrated yards that were part of case study IV (see Table 7 and paper 3), and an increased level of detail in the yard type descriptions. Building on the work in this thesis, we see this as a natural next step to further advance the field of yard logistics.

Additional research efforts are also needed to further generalize the findings of this thesis to other ETO sectors apart from yard operations. For instance, research methodologies could be applied that allow further generalization of the findings of the current study. Furthermore, future research should compare yard logistics with similar logistics contexts.

As part of the research in this thesis, a wide range of different yard logistics challenges have been identified across different types of yard operations. Although digitalization has been suggested as one possible way of addressing certain challenges, future research should focus on solutions that are operationally, technically, and commercially sound.

While paper 4 investigated how the applicability of Industry 4.0 technologies differs between manufacturing environments, the applicability across different yards has not been studied. Building on the research on yard logistics digitalization in this thesis, further work should investigate both the need for digitalization in different types of yards as well as the applicability of digital technologies in different yard logistics contexts.

Regarding the digitalization of yard logistics, there are several opportunities for further research. First, we see potential in extended research on the maturity of digitalization in yard logistics. The overview of the current state of digitalization in yard logistics and the proposed concept for digitalized yard logistics could serve as the foundation for the development of a maturity model for assessing digitalization levels and identifying opportunities for improving yard logistics through digitalization. In addition, there is a need for further research on how the concept of digitalization of yard logistics, presented in sub-section 4.2.5, can be realized and implemented. As stated in section 6.3, a key next step is to obtain insights and feedback from practitioners in the field as well as technology providers regarding the proposed concept. Finally, further research should aim to develop more concrete descriptions of how digital technologies can be implemented in the case yards, including more extensive analyses of the benefits in terms of relevant and measurable performance indicators, such as time, cost, flexibility, and quality, allowing comparisons to be made across the possible technological solutions.

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Appendix A: Case study protocol

Introduction

This protocol describes the data collection and field procedures to be followed for each case study.

Pre-Visit Preparation

For yards where a contact person already has been identified an email should be sent to this person. For yards where a contact person has not yet been identified, the yard manager, logistics manager, supply chain manager, or a person in equivalent position of the chosen yard should be contacted by email. In either case, the contact person should be sent a general description of the study and areas to be addressed.

Each participating yard will be the object of a case study involving at least one visit to the yard for at least one day, including interviews. If necessary, the data collection from the visit may be complemented through follow-up interviews over Skype, phone, or email.

Before the visits to each yard, archival sources such as available open sources of data should be studied to provide background information on the company and the yard. These may include company website and reference list, annual reports, news articles, financial databases (e.g., www.proff.no) and general information about the industry.

Data sources

Data should be collected from the following main sources:

- Interviews
    - Semi-structured interviews and discussions with company representatives
- Direct observations
    - Site tour of the yard, focusing on the logistics and material flow
- Archival records:
    - Open sources of data: Industry reports and magazines, online databases, Product catalogs and information from company website, annual reports, Google maps etc.
- Existing documentation

On site data collection

Data collection on site should focus on the current yard operations, with its current product/vessel types and related activity.

The researcher should collect information in five main areas:

1) Yard information
2) Business context/environment and strategy
3) Manufacturing logistics
    a) Facilities and resources
    b) Processes and flows
4) Use of digital technologies
5) Additional information enabling the understanding and enrichening of the collected data.

The following tables shows the topics and questions to be addressed within each of the areas 1-5. For each topic the respective Unit of Measurement (UoM) and the data sources used is indicated.

1. Yard information

Topic	UoM	Questions	Data sources
Yard type	Yard	- Outfitting yard, hull yard, repair yard, fully integrated yard	- Open sources - Interviews
Main product categories	Yard	- Vessel types produced	- Open sources - Interviews
Degree of product customization	Main product types	- Degree of product customization - How predictable is the customization? - What are the main consequences of customization to manufacturing and logistics?	- Interviews - Direct observations - Open sources
Total production volume	Yard	- Yearly production volume in units - Yearly sales value of production	- Interviews - Open sources
Yard size	Yard	- Number of production workers o Own employees o Sub-contractors	- Interviews
Manufacturing logistics performance	Yard	- Throughput time of a customer order, from production start to completion (Rough estimate) - Man hours (rough estimate per product/vessel type)	- Interviews
Importance of yard logistics	Company	- In the big picture, how important is the internal logistics at the yard for the overall performance of the company?	- Interviews

2. Business context/environment and strategy

Topic	UoM	Questions	Data sources
Business environment	Company	- Key characteristics of the business environment (industry, growth rate of the markets served, market share etc.) - Major changes in customer demands and business condition in past few years	- Open sources - Interviews
Order winners and order qualifiers	Yard	- Order winners: - Order qualifiers:	- Interviews
Competitive strategy	Company / Yard	- Markets the company competes in, types of customers (industry, size,) - How the company competes in the market: o Market coverage: few vs. many markets o Customer focus: few vs many customers	- Interviews - Open sources
Product design	Yard	- Use of own design vs. external ship design	- Interviews
Build strategy / Offshoring strategy	Yard	- Production stages performed at other shipyard: o Steel block construction, block outfitting, Ship assembly, Dock outfitting, Quay outfitting, Commissioning, and testing - Degree of advanced outfitting, e.g., percent outfitting blocks complete before ship assembly - Number and size of blocks the ship is assembled from (few and large vs many and small)	- Interviews - Open sources
Supply network	Company / Yard	- Characteristics of the supply network (partnerships, vertical integration etc.) o Relationship/integration with offshore shipbuilder o Relationship/integration with main equipment suppliers o Relationship/integration with ship designer o Relevant relationships/integration with other actors	- Interviews

3a. Manufacturing logistics: Facilities and resources

Topic	UoM	Questions	Data sources
Quay, docking and slip facilities	Yard	- Graving dock, floating dock, dock hall, quay, ground level system, slipway	- Interviews - Direct observations - Open sources

Other yard facilities (physical layout)	Yard	- Storage areas and warehouses etc. at site
		  o Type/function
		  o Size
		  o Location
		  o How is it operated?
		- Fabrication and workshop facilities (steel fabrication, pipe fabrication etc.)
		  o Type/function
		  o Size
		  o Location
		  o How is it operated?
		- Administrative buildings and facilities
		- Workers' facilities (toilets, break rooms, cafeteria)
		- Other shops for outfitting work (painting and sandblasting, welding, shops for cutting, bending, rework)
		- Support platforms for ship access during dock/quay outfitting
			- Interviews
			- Direct observations
			- Open sources

Other logistics resources at yard	Yard	- Cranes, vehicles, trucks, carts, automated storage or feeding systems etc.	- Interviews - Direct observations - Open sources

3b. Manufacturing logistics: Processes and flows

Topic	UoM	Questions	Data sources
Production changes and interruptions	Yard	- How are product or project changes affecting production and operations at the yard?	- Interviews
Type of work	Yard	- Which tasks are typically dependent on unique operating procedures (work instructions, drawings etc.)? - Which tasks are typically dependent on the skills of the operator? - The use of operating procedures (work instructions, drawings etc.): o How are they distributed? o Where are they generated and sent from?	- Interviews - Direct observations
Material flow / Transport management / Materials management	Yard	- How is material transported around the yard? Cranes, vehicles, trucks etc. [Transport management] - How is material moved onto the vessel? - How is the material flow controlled? o What determines and triggers the movement of material from A to B? o Description of how material is acquired from storage (or similar location) to place of production ▪ How is information given to the worker who will perform the task? Is the task tracked? If so, how? ▪ Is the information sufficient for the worker to perform the task, or can it result in additional information needs?	- Direct observations - Interviews
Information flow	Yard	- Process descriptions: o of the information flow to and from the yard site (typically between higher level planning and the foremen) and o internally at site (typically to and from the workers) - Foreman checks daily in the planning system what is to be done? - What are the main tasks of the foremen? - Morning meeting to distribute jobs? - How is production progress reported? At the end of each day? Manually/automatically? - How are shift activities and jobs planned, and what are the operators' role in this?	- Interviews - Direct observations
Logistics planning and control (intralogistics)	Yard	- Control areas (e.g., main storage, pipe workshop etc. – how operations in these are planned and controlled) - Planning and control systems used (PLM, ERP, MES, SCADA etc.) o Are the systems working as they should?	- Interviews - Direct observations
Manufacturing logistics challenges	Yard	- What are the main manufacturing logistics challenges at the yard?	- Interviews - Direct observations

4. Digitalization and the use of digital technologies

Topic	Unit of measurement	Questions	Data sources
Strategic initiatives or projects on digitalization	Company	- Have the company launched any strategic initiatives or projects on the topic of digitalization or similar? - Are there any positions designated to working on digitalization?	- Interviews
Level of digitalization	Yard	- Are any of the listed technologies implemented? (See table) - If so, how are they used? For which processes?	- Interviews - Direct observations
Operator support	Yard	- Are any support tools used by operators? (E.g. smartphone, tablets, smart glasses) - If so, are all operators using the same support tools, or is it distributed depending on type of work or similar?	- Direct observations - Interviews
IT system integration	Yard	- How is data from shop floor registered and transmitted to high level planning systems? o Data entry by foreman or by operators? - How is data collected from shop floor?	- Interviews - Direct observations
Acquisition and implementation of technology	Yard	- Acquisition strategy o From technology providers or in-house developments? - Implementation strategy o Pilot projects?	- Interviews
Plans for digital technology implementation	Yard	- Are there any concrete plans for investing in and implementing digital technologies in the coming years?	- Interviews

5. Additional information enabling the understanding and enrichening of the collected data

What are the main barriers to the adoption of digital technologies (Industry 4.0 technologies)?

What are the prerequisites that must be in place for technology implementation?

Table 1: Barriers to the adoption of Industry 4.0 technologies.

#	Barriers	Meaning	Impact: 1-5
1	High investment in Industry 4.0 implementation	High amount of capital investments needed in order to implement the industry 4.0 initiatives.	
2	Lack of clarity regarding the economic benefit	Productivity gains and economic benefits of technological implementation are unclear due to fragmented implementation across the value chain.	
3	Challenge in value chain integration	Difficult to break the silos across various departments within the organization as well as among different organizations in the value chain.	
4	Risk of security breaches	Highly interconnected systems providing more exposure for hackers to attack, and firms concerned about sharing data with third party software providers.	
5	The low maturity level of the desired technology	Technology pieces deployed at their premature stage resulting in system failure as well as chaos across the value chain as the systems are interconnected.	
6	Inequality	Industry 4.0 will worsen the gap between the rich and the poor, the developed and the developing nations and the young and the old.	
7	Disruption to existing jobs	Developing nations like India, China and others where cheap labor is the key resource would face a hit with technological advancements.	
8	Lack of standards, regulations and forms of certification	There is a lack of standards and government regulation across the industries embracing industry 4.0.	
9	Lack of infrastructure	Industry is not ready with all the technological infrastructure needed with every stakeholder in the value chain. Big players might do but players with medium to small capabilities would struggle.	
10	Lack of digital skills	Employees and the workers in the industry need training and development to upgrade their technical skills set.	
11	Challenges in ensuring data quality	Large volume of data gathered through various technology used in Industry 4.0 leads to difficulty in extract the useful data	
12	Lack of internal digital culture and training	An internal culture to embrace technological advancements has to be nurtured from top to bottom in the organization and make the teams technology-ready.	
13	Resistance to change	Firms performing operations in conventional ways for years have a natural tendency to resist the changes.	
14	Ineffective change management	Ineffective management of changing processes by employees, executives, third party channel partners, value chain members.	
15	Lack of digital strategy alongside resource scarcity	Firms who have no strategical roadmap to analyze, develop and execute the capability building exercise and firms lacking resources to do so would suffer in Industry 4.0 environment.	

If any digital technologies have been implemented:

- When was it implemented?
- How was the implementation process?
- Was the implementation a result of own development (in-house) or purchased from a technology provider?
- Where did the idea come from? Was there a specific, identified problem, or was the implementation more experimental to test a new opportunity?
- Why was the project/initiative and implementation initiated? And why for the selected process(es)/departments/areas?
- What are the difficulties or problems experienced after implementation, if any?
- How far has the implementation process come?
- What type of financing was used?

Other initiatives/projects/improvement efforts not related to digitalization:

- E.g., Lean, automation, process technology
- Does such initiatives have better “standing” than digitalization? Is the company more in favor of the more traditional improvements?
- Are they less capital intensive or involves a lower risk?

Table 2: Overview of relevant digital technology groups.

Technology groups	**Description**
Additive manufacturing	3D printing of objects layer by layer, based on 3D models or CAD files of the objects
Autonomous robots	Automatic Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), and Collaborative robots (COBOTS) for material handling and performing logistics tasks
Cloud manufacturing	Cloud-based solutions for sharing and exchange of data between systems, sites, and companies.
Cyber security	The secure and reliable protection of industrial production systems from cyber threats.
Data analytics	Transforming data into knowledge and actions within a manufacturing system. • Big data for analysis of large data sets • Artificial intelligence • Machine learning • Advanced simulations
Integration of IT systems	Horizontal and vertical integration of IT systems for production management (PLM, ERP, MES, SCADA, shop floor system etc.)
Internet of Things	Objects equipped with sensors and actuators, enabling storing and exchange of information (Example: RFID tagging of products)
Visual technology	The visual representation of an object or item, in the form of augmented reality (AR) through superimposing a computer-generated 3D image in the real world, creating a virtual reality (VR) or projecting 3D images as hologram.

Post visits stage

A report should be produced as soon as possible after each yard visit. It should contain all relevant notes and collected data. The report should also include any reflections by the researcher that may be of interest to each of the yards.

Draft letter requesting participation in the study

Topic: Next generation yard logistics – a current research study by NTNU

Dear […]

The Production management research group at NTNU is currently carrying out a study of yard logistics. The research involves a series of case studies of shipyards and EPC yards with the overall aim to develop knowledge on the current state of yard logistics, opportunities of digitalization and outline the directions for the next generation yard logistics.

We would highly value an opportunity to include your yard in our study. Including your yard in our study would involve one or more visits to the yard, in addition to conducting a couple of interviews with key persons with knowledge of the yard and its operations. The lessons learned from studying your yard and other yards will be used to provide tailored feedback to your company, as well as a report of the main findings of the research project.

In our research, we are interested in discussing with you how the internal logistics at the yard is organized, planned, coordinated and controlled, and any digital solutions you have in place for such tasks. The yard or the company's general view on digitalization is also of interest.

A short presentation of the research project has been enclosed.

Full confidentiality will of course be respected. All data collected in this research will remain at NTNU and will not be disseminated in such a manner that it identifies participating yards. As NTNU employees we are already part of a confidentiality agreement, but we will willingly sign any other confidentiality agreements you may find necessary.

We will contact you again in the near future to discuss your participation in the study.

Thank you for your cooperation.

Yours sincerely,

Jo Wessel Strandhagen
Marco Semini
Erlend Alfnes

Collection of papers

Paper 1

Strandhagen, J. W., Semini, M. & Alfnes, E. (2022). Yard logistics: Characteristics and challenges. Submitted to the *International Journal of Production Research.*

This paper is awaiting publication and is not included in NTNU Open

Paper 2

Strandhagen, J. W., Andersen, B., Semini, M. & Alfnes, E. (2022). Performance measurement in engineer-to-order yard logistics. Submitted to the *International Journal of Productivity and Performance Management.*

This paper is awaiting publication and is not included in NTNU Open

Paper 3

Strandhagen, J. W., Jeong, Y., Woo, J. H., Semini, M., Wiktorsson, M., Strandhagen, J. O. & Alfnes, E. (2020). Factors affecting shipyard operations and logistics: A framework and comparison of shipbuilding approaches. In: B. Lalic, V. Majstorovic, U. Marjanovic, G. von Cieminski, & D. Romero (Eds.) *Advances in Production Management Systems. Towards Smart and Digital Manufacturing. APMS 2020. IFIP Advances in Information and Communication Technology* (Vol. 592, pp 529-537): Springer.

Factors Affecting Shipyard Operations and Logistics: A Framework and Comparison of Shipbuilding Approaches

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Abstract. Shipyards around the world have several differences that affect the logistics processes at each yard. The purpose of this paper is to develop a framework for mapping the key factors affecting shipyard logistics. We test and validate the framework by applying it to three case shipyards—one Norwegian and two South Korean. To develop the framework, we first identify key factors affecting shipyard logistics, based on a review of the existing literature. The framework is then applied using data from the three cases. Through a comparative analysis of the collected data, we identify and outline the main logistics differences and the key factors' main implications for the shipyards. The findings from the analysis indicate that there are important differences between the shipyards, and these have implications for their scope of planning and execution of shipyard activities, their primary focus of coordination, and their primary flows, among others. Through the framework development and comparative analysis, the paper contributes to an enhanced understanding of shipyard logistics, as well as how it is affected by internal and external yard characteristics.

Keywords: Shipbuilding · Shipyard · Logistics · Engineer-to-order manufacturing

1 Introduction

The shipbuilding industry is currently under strong economic pressure, and the drastic reduction in the oil price, from around 2015, caused significant changes in the global shipbuilding market. Fierce global competition has driven the margins of shipbuilding companies down, making cost-efficient operations more important than ever before. Efficient shipyard logistics—defined here as the coordination of shipyard operations related to the flow of materials through a yard up to the completion of a ship—is, therefore, increasingly significant. However, research on the topic remains scarce. Shipyards also operate under differing conditions, which affect the logistics processes

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at yards. Increased knowledge of the factors that affect a shipyard's logistics activities can increase the understanding of how to achieve efficient yard logistics. Norway and South Korea are examples of two strong, but different, shipbuilding nations. Norway, with its long coastline, has strong traditions in the shipbuilding industry, which remains an important industry for the country [1]. Due to Norway's high labor costs, competing on price is difficult. Norwegian shipbuilding has focused on the low volume production of high-quality, highly customized vessels, with innovative features, for the offshore industry. South Korea, on the other hand, with lower wages and strategic government support, has become a leading shipbuilding nation through the higher volume production of large tankers and cargo carriers [2]. Accordingly, contextual factors affect how shipbuilders should approach their shipyard logistics.

The existing literature includes various studies comparing different aspects within shipbuilding. Eich-Born and Hassink [3] conducted a comparative analysis of shipbuilding regions in Germany and South Korea, focusing on how local, regional, and national factors affect global competition. Bai et al. [4] compared the information technology, production technology, and local characteristics of Chinese, Korean, and Japanese shipyards, albeit without a structured framework. Pires Jr. et al. [5] presented a methodology for shipbuilding performance assessment, based on yard characteristics, production patterns, and industrial surroundings. Colin and Pinto [6] analyzed the asset turnover of several shipbuilding companies, while Semini et al. [7] compared different offshoring strategies in ship production. Despite the range of shipbuilding studies, there is a lack of studies aimed at shipyard logistics.

This paper addresses the need for an increased knowledge of the factors that affect a shipyard's internal logistics. The purpose of this paper is to develop a framework for mapping the key factors affecting shipyard logistics. Such a framework may enable comparative analyses of shipyards and provide useful descriptions of the characteristics and challenges related to shipyard logistics. We test the framework by applying it to a Norwegian shipyard and two South Korean shipyards.

2 Research Approach and Framework Development

Figure 1 shows the overall research approach taken in this study. The first step in developing the framework was to identify the relevant factors affecting shipyard logistics, based on a literature review. Following the factor identification, and inspired by Jonsson and Mattsson's [8] original planning environment framework, we developed the framework by establishing the factors and their respective items and content. The framework was then applied to map three different shipyards: Ulstein Verft AS (UVE), Hyundai Heavy Industries Ulsan (HHI Ulsan), and STX Offshore and Shipbuilding Jinhae (STX Jinhae). The first is a Norwegian newbuilding shipyard, and the next two are large and medium-sized shipyards in South Korea. The authors' strong relationship with the case shipyards allowed access to data through interviews and site observations, and various yard documentation and records were made available to the authors. The data collection also provided new insights that were used to revise and improve the framework. Therefore, the framework development became an iterative process with new revisions, as data from the cases were collected and analyzed. The final step was to conduct a cross-case comparative analysis, based on the mapping of the shipyards, and discuss the findings of the analysis.

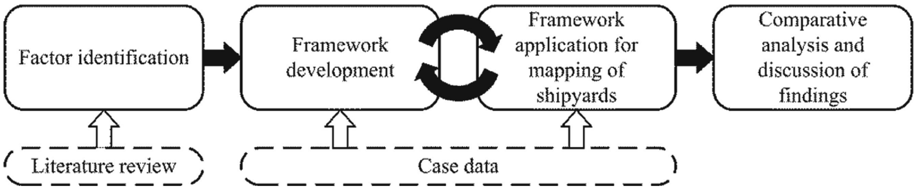

Fig. 1. The paper's research approach.

From an operations management perspective, shipyards are different from traditional manufacturing systems, due to the distinct characteristics of their production environment. Following Buer et al.'s [9] definition of production environment, we define a shipyard logistics environment as the sum of internal and external factors that affect shipyard logistics processes. Based on the literature, we include four factors: yard characteristics, product and market characteristics, process characteristics, and supply chain characteristics. Each factor consists of several items.

As shipyards are different from traditional manufacturing systems, we treat yard characteristics as a separate factor. First, a yard's facilities and available equipment influence both the activities that can be carried out and how they can be carried out. Second, shipbuilding is the production of large-scale products that require a certain amount of physical space and number of workers. Although shipbuilding is typically characterized as production in a fixed-position layout, several options exist within that main layout type, eventually affecting how material flows through a shipyard. Finally, a yard's logistics is affected by its levels of process automation and information technology (IT) in terms of IT systems to support logistics processes.

A production environment's product and market characteristics typically include the placement of the customer order decoupling point, product volume and variety, level of customization, and product complexity. However, the description of a shipyard requires items that are adapted to the shipbuilding context. Shipyards can vary based on the types of vessels they produce, as different types may require different material handling equipment or different organization of the activities at a shipyard. The vessel type can also indicate the complexity associated with building it. The number of vessels produced per year and whether a shipyard typically produces one-offs or a series of several ships per order are additional aspects that affect shipyard logistics.

A yard's process characteristics include the main shipbuilding processes it performs, as processes may be outsourced to other yards. There are also different possible building practices for outfitting operations in shipbuilding, i.e., the installation of a ship's equipment in its hull. As the hull is typically constructed by joining hull blocks together, outfitting may be done on single blocks before they are joined to erect a ship. Outfitting after ship erection reduces accessibility to the point of installation, as the hull is then a closed structure. The final item within this factor is the throughput time, i.e., the total time from production start to ship completion.

Shipyards may differ greatly in how their supply chains are organized. The degree of vertical integration has been found to have a particularly significant impact on shipbuilding productivity [10]. Thus, it is included as an item within supply chain characteristics. A shipyard's supply network, in general, may also influence its logistics and is, therefore, included as a second item within this factor.

The framework is shown in Table 1. In addition to the four factors included in the framework, different organizational, social, and cultural factors may affect shipyard logistics. These factors include labor costs and productivity [2, 5], organizational structure [11], and characteristics of the workforce [2]. They are particularly relevant when comparing shipyards in different countries, but they are not included as distinct factors in the mapping framework. Similarly, economic factors, such as the shipbuilding company's financial performance and eventual government support [2, 5], while relevant factors, are not included in the framework at the current stage.

Table 1. Framework for mapping factors affecting shipyard logistics.

Factors	Items	Content	Ref.
Yard characteristics	Yard facilities	Main production facilities, docks, and quays	[6]
	Yard equipment	Main yard equipment for material handling	[5]
	Yard size	Total number of shipyard workers, total yard area	[10]
	Yard layout	Shape and direction of material flow through the yard	[2]
	Automation level	Level of automation of shipbuilding processes	[6]
	IT level	Level of IT systems infrastructure and integration	[5]
Product and market characteristics	Vessel types produced	Tankers, bulk carriers, cargo/passenger ships, fishing vessels, and offshore vessels	[12]
	Customization	Degree of customization	[13]
	Total production volume	Average number of vessels produced per year	[9]
	Order size	Average number of similar ships per customer order	[9]
	Type and size of market	Type and size of the market the shipyard competes in	[2]
Process characteristics	Throughput time	Average throughput time of a customer order	[9]
	Main shipbuilding processes	Main shipbuilding processes performed at own shipyard	[7]
	Building practices	Degree of advanced outfitting	[12]
Supply chain characteristics	Supply network	Characteristics of the supply network	[5]
	Vertical integration	Shipyard's integration with hull yard, ship designer, main equipment suppliers, and shipowner	[10]

3 Framework Application: A Comparison of Shipyards in Norway and South Korea

Norway's high cost levels affect performance, especially in labor-intensive production, by driving up product costs through higher direct and indirect labor costs [14]. A consequence of this is the offshoring of most steel-related tasks to countries with lower cost levels [7]. Therefore, Norwegian yards primarily perform the more advanced outfitting tasks, such as the installation of machinery and deck equipment, electrical systems, and accommodation, while the steel structure is built in lower-cost countries [7]. With these high cost levels, there is also a need to focus on high value-added and knowledge-based products, making access to competence and innovation vital. Norway's maritime industry is supported by a network of maritime clusters, and proximity to customers, suppliers, competitors, and research institutions provides benefits that compensate for the high labor costs [14]. Organizational, social, and cultural factors also have implications for the Norwegian shipbuilding industry. Examples include the flat and informal organizational structures, autonomous employees, a skilled workforce, and the small local communities [14]. These locational characteristics provide Norway with a competitive advantage in the production of highly customized products of high quality and with innovative features. This has enabled Norwegian shipbuilders to be global leaders in the market for highly specialized offshore vessels. The performance of Norwegian shipyards has been affected by fluctuations in the oil and gas market, which has forced them to pursue, and adapt to, alternative markets [15].

After entering the shipbuilding industry in the 1970s, South Korea has strengthened its position as a leading shipbuilding nation through lower wages and a national strategic focus [2]. The country's shipbuilding industry has benefited from the large domestic production of steel and a strong marine equipment industry [16], and their large shipyards have dominated for the past decade [2]. South Korean shipyards produce a variety of different ship types, with the main types being larger vessels, such as container ships and various tankers [16]. South Korea's dominance in the shipbuilding industry is a result of advanced technological developments, innovation, and governmental research and development support, in addition to the potential to compete on price. However, the fierce global shipbuilding environment also challenges South Korea, and with many shipyard's struggling to stay in business, the national industry is currently seeing significant restructuring, through several mergers between shipbuilding companies.

Table 2 shows the mapping of the three case shipyards after the application of the framework. The main differences and their implications for logistics are discussed in Sect. 4.

Table 2. Framework application on the three case shipyards.

Items	UVE	HHI Ulsan	STX Jinhae
Yard facilities	Pipe fabrication, outfitting, painting; quay (208 m), 1 graving dock	Steel and pipe fabrication, assembly, outfitting, painting, pre-erection, erection; quay (7.4 km), 10 graving docks	Steel and pipe fabrication, assembly, outfitting, painting; pre-erection, erection; quay (1.8 km), 2 graving docks
Yard equipment	2 main traveling cranes (250 tonnes), 4 dockside and quayside cranes	9 goliath cranes (max 1,600 tonnes), 33 transporters	4 goliath cranes, 6 transporters
Yard size	Around 75,000 m^2 and 300 shipyard workers	Around 6,320,000 m^2 and 15,000 shipyard workers	Around 1,000,000 m^2 and 1,000 shipyard workers
Yard layout	L-shaped, with material flow directed towards hull in dock or at quay	U-shaped from steel entry through fabrication, assembly, and erection to docks and quaysides	
Level of automation	Mostly manual operations, with some automation of fabrication	High automation of steelwork and block assembly. Mostly manual operation on painting, outfitting, and ship erection	High automation of steelwork and medium automation of block assembly. Mostly manual operation on painting, outfitting, and ship erection
IT level	IT systems used for all business processes but with a low level of integration between systems	IT systems used for all main business processes. High level of integration in the design phase. Low integration at the production site	
Vessel types produced	Offshore support vessels (PSV, OCV, SOV) and passenger ships (ROPAX, cruise)	Large size commercial carriers, offshore platform systems, and support vessels	Tankers, gas carriers, cargo carrying vessels (container ships, bulk), and LNG bunkering
Customization	Very high	Very high	Very high
Total production volume	2 vessels per year	70 vessels per year	10 vessels per year
Order size	Few—between 1 and 2	Several—up to 20	Several—up to 10
Type and size of market	Mainly offshore, cruise, and passenger markets	Maritime transport market and offshore market	Maritime transport market

(*continued*)

Table 2. (*continued*)

Items	UVE	HHI Ulsan	STX Jinhae
Throughput time	20 months	10 months	12 months
Main shipbuilding processes	Outfits complete hull structures in dry dock and at quayside	Performs all main processes at own shipyard (integrated yard)	Performs all main processes at own shipyard (integrated yard)
Building practices	All outfitting work performed on closed hull	Pre-outfitting of hull blocks	Pre-outfitting of hull blocks
Supply network	Hull production at a yard in Poland. Mostly local equipment suppliers	Domestic and foreign suppliers of steel. Partly outsourced hull block construction. Two engine suppliers. Several domestic suppliers of other equipment	
Vertical integration	Medium. Vertical integration with ship designer. Partnership with hull yard in Poland	Very high. In-house ship design. Vertical integration with main equipment suppliers	Low. Some in-house design-activity

4 Discussion

One of the main differences between the three yards studied concerns the shipbuilding processes performed at each yard. UVE mainly performs outfitting operations, with the other main shipbuilding processes performed at a partner yard. From a logistics perspective, UVE can keep its focus on the outfitting operations. However, as ships spend only a part of the total construction time at UVE's yard, it must operate with a tighter schedule, as there is less room for flexibility in the planning and execution of the outfitting activities performed at their yard. HHI Ulsan and STX Jinhae, on the other hand, are fully integrated yards, and must coordinate the whole range of shipbuilding processes and handle the logistics activities related to these processes.

Another main difference is the large variation in production volumes between the yards. While they all build customized vessels, UVE is more focused on building highly specialized vessels, in a market with lower global demand, than the South Korean yards. While UVE mostly produces one-offs, the South Korean yards build series of several ships. One implication for logistics is the total number of ships being built at the respective yard at any given time. Having up to 20 ships at the yard at a time requires significant interproject coordination, i.e., coordination between projects. UVE mainly has to focus on intraproject coordination, i.e., coordination within each shipbuilding project, as each project makes up a higher share of the total sales value.

The yards' production volumes are naturally linked with their capacity in terms of the number of docks, number and lifting capacity of cranes, and the yards' sizes. Producing tens of ships per year requires the facilities and space of a different magnitude compared to the production of only a handful of ships. As HHI Ulsan and STX Jinhae, both integrated shipyards, perform all the main shipbuilding processes, they need equipment and transporters that can handle and move hull blocks. For instance, yards of the size of HHI Ulsan typically have around 500 hull blocks located at different areas of their yard, and every day more than 100 blocks are transported. UVE, on the other hand, only performs outfitting operations on complete hulls. It does not need heavy-duty material handling equipment, as there is no transportation of hull blocks. The heaviest material handling process at UVE is the lifting of equipment by tower cranes for installation on ships in the dock or at the quay. Accordingly, UVE's main concern regarding layout-related issues is how to improve productivity in their outfitting operations. The primary flow that UVE has to plan and control to perform outfitting operations is the flow of workers to and from the dock or quay and on and off the ship being built. The South Korean yards are, to a larger extent, concerned with planning and controlling the flow of blocks and larger ship structures around their yards.

5 Conclusions, Limitations, and Further Research

This paper has proposed a framework for mapping the key factors affecting shipyard logistics. Yard characteristics, product and market characteristics, process characteristics, and supply chain characteristics have implications for a shipyard's logistics, and this has been illustrated through mapping three shipyards by applying the framework. The factors' key implications for shipyard logistics include the scope of planning and execution of shipyard activities, the primary focus of coordination (intraproject versus interproject), and the yards' primary flows.

The low number of cases is one of the paper's limitations. A larger number of cases would enhance the generalizability of the results. Moreover, the presented framework is focused on the shipbuilding industry and the shipyard environment and is currently a first version that needs additional work to be developed further. Future work should consider comparing shipyards with the production environments in other industries.

Nevertheless, the paper contributes to an enhancement of the understanding of shipyard logistics, as there is a lack of related research in the shipyard logistics area, and addresses how logistics challenges are affected by internal and external yard characteristics. The results of this paper can help shipbuilders understand the internal logistics environment and support them in selecting and designing appropriate logistics planning and management systems. The paper offers a guide to further research, which should aim to investigate the main logistics challenges in different shipyard contexts, with the specific objective of developing a typology of shipbuilding logistics. The future work on shipyard logistics should also address how the need for digitalization and the use of Industry 4.0 technologies differs, based on shipyard logistics differences.

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Paper 4

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The fit of Industry 4.0 applications in manufacturing logistics: a multiple case study

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Abstract The fourth industrial revolution, Industry 4.0, is expected to cause disruptive changes in industrial production. It is driven by rapid technological developments and the need for manufacturing companies to make themselves independent of high labor costs. Industry 4.0 concerns several aspects of industrial production, including manufacturing logistics, business models and products and services. The applications of Industry 4.0 have been vastly outlined. However, the fit of Industry 4.0 applications in different production environments is not clear. The purpose of this paper is to identify and investigate the Industry 4.0 technologies that are applicable to manufacturing logistics, and how the production environment influences the applicability of these technologies. This is done through a multiple case study of four Norwegian manufacturing companies. The findings from the study indicate that the applicability of Industry 4.0 in manufacturing logistics is dependent on the production environment. Companies with a low degree of production repetitiveness see less potential in applying Industry 4.0 technologies in manufacturing logistics, while companies with a highly repetitive production see a higher potential.

Keywords Industry 4.0 · Manufacturing logistics · Production planning and control · Production environment

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1 Introduction

The fourth industrial revolution, Industry 4.0, is expected to cause disruptive changes in industrial production. Originating from the German strategic initiative Industrie 4.0 [1], it is now on the agenda in several European countries and in the US and Asia. It is built around rapidly developing technologies and concepts, e.g., the Internet of things (IoT), and is expected to lead to a paradigm shift in industrial production. To remain competitive, Norwegian manufacturers and manufacturers in countries where labor costs are high should explore the concept of Industry 4.0 to enable exploitation of the specific benefits it can offer in terms of new solutions for industrial production and logistics.

Industry 4.0 is a broad term, used within several different fields of study, and its scope covers the entirety of industrial manufacturing. This can make it difficult to grasp, for both academia and practitioners, thus breaking it down and investigating it in the context of manufacturing logistics will make it more conceivable.

In the context of this paper, “manufacturing logistics” concerns the planning, control and configuration of logistics flow in a manufacturing company. The terms “manufacturing” and “production” are in this paper used as two interchangeable terms. How manufacturing logistics should be handled is dependent on the company’s production environment [2, 3]. The production environment is here considered as the set of variables that describes the market related, product related and production process related characteristic features of a company. Industry 4.0 will have implications for industrial processes and value creation [1], and it includes several aspects relevant for manufacturing logistics. This leads to the hypothesis that the applicability of Industry 4.0 technologies in manufacturing logistics is dependent on the company's production environment. If Industry 4.0 is to improve manufacturing logistics performance, there are reasons to believe that the production environment will have a major impact on what aspects of Industry 4.0 should be approached for a specific company and how these should be approached. Moreover, recent years' research papers, governmental reports and strategy plans, media reports and popular science articles outline numerous applications of Industry 4.0. However, it is not well documented which applications will fit in which production environment. Thus, this paper sets out to investigate the fit of Industry 4.0 applications in manufacturing logistics when considering the characteristics of companies' production environment.

Two research questions have been formulated: (i) What are key applications of Industry 4.0 technology in the context of manufacturing logistics? (ii) How is the applicability of these technologies affected by the production environment?

Through answering these research questions, this paper aims to contribute to the existing theory on production environments, by investigating the relationship between applications of Industry 4.0 technology and production environments. The main contributions include the identification and classification of Industry 4.0 technologies for manufacturing logistics, an empirical analysis of the case companies and their production environment, as well as a proposition regarding the fit of Industry 4.0 applications in manufacturing logistics.

This paper is an extended version of "Importance of production environments when applying Industry 4.0 to production logistics—a multiple case study", presented at the 6th International Workshop of Advanced Manufacturing and Automation (IWAMA 2016). The rest of the paper is structured as follows. Sections 2–4 will cover the theoretical background of relevant topics. Further, the methodology used in conducting the case studies is presented in Sect. 5. A presentation of the case companies and findings from the case studies are provided in Sect. 6, followed by a discussion of the findings in Sect. 7. Conclusions, limitations and further research are provided in Sect. 8.

2 Concept of Industry 4.0

Industry 4.0 can be described as an umbrella term, referring to a range of current concepts and touching several disciplines within industry [4]. The key drivers for this fourth industrial revolution can be divided in two aspects. The first is the combination of rapidly advancing technological developments of today, including IoT, Internet of services (IoS), cyber-physical systems (CPS), smart objects and big data. Such technologies may result in a paradigm shift in industrial production [4], and this can be described as a technology push. The second aspect is the demand from manufacturing companies, especially in countries with high cost levels, to make themselves independent of high labor costs by exploiting new technology. Businesses will seek new ways of offering their products and services, and even new business models will emerge [1]. Hermann et al. [5] provided the following definition of Industry 4.0: "Industry 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured smart factories of Industry 4.0, CPS monitors physical processes, creates a virtual copy of the physical world and makes decentralized decisions. Over the IoT, CPS communicates and cooperates with each other and humans in real-time. Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain."

2.1 Three types of integration

As described in Refs. [1, 6, 7], Industry 4.0 consists of three main features. These are three types of integration, which are expected to be the reality in future production networks. They are introduced in the following three paragraphs.

Vertical integration concerns the integration of various IT systems at different hierarchical levels inside a factory [1]. Wang et al. [6] emphasized the essentiality of vertically integrating the levels of the automation pyramid, from sensors and actuators on the shop floor, up through the manufacturing execution system (MES) and further up to the enterprise resource planning (ERP) level. This will enable a flexible and reconfigurable manufacturing system [6, 7]. Such a vertical integration, with expanded utilization of planning tools, software and IT and digitalization of manufacturing has been stated as a requirement to ensure continued competitiveness for European manufacturing industry [8].

Horizontal integration through value networks will facilitate inter-corporation collaboration where material flows fluently among these corporations [6]. This integration describes the cross-company and company-internal intelligent cross-linking and digitalization of value creation modules [9]. Brettel et al. [7] pointed to the trend of decreasing depth of added value within one factory as an enabling factor for introducing collaborative manufacturing and collaborative development environments. These are concepts where companies organize in networks in order to exploit fully the core competencies of every manufacturer within the network [10].

End-to-end engineering integration across the entire value chain will support the increasing requirements regarding product customization [6]. It includes cross-linking of stakeholders, products and equipment along the product life cycle, from raw material acquisition to end of life [9]. Brettel et al. [7] argued that value added services would become leverage opportunities to ensure a strong competitive position.

2.2 Components of Industry 4.0

Kagermann et al. [1] and Hermann et al. [5] identified three components of Industry 4.0. These are CPS, IoT and smart factory. These will be described in the following three subsections.

2.2.1 CPS

The fourth industrial revolution builds upon the implementation of CPS, which features end-to-end ICT-based integration [1]. Lee [11] described CPS as integrations of computation and physical processes, with embedded computers and networks monitoring and controlling physical processes. It can be considered as the merge between the physical and digital world [4]. In the manufacturing context, CPS comprises smart machines and production facilities that are capable of autonomously exchanging information, triggering actions and controlling each other independently [1]. Lee et al. [12] described the two main functional components of a CPS:

(i) The advanced connectivity that ensured real-time acquisition of data from the physical world and information from the cyber space.
(ii) Intelligent data management, analytics and computational capability that constructed the cyber space.

Hermann et al. [5] defined three characterizing phases in the development of CPS, which were (i) identification technologies (e.g., RFID), (ii) sensors and actuators with a limited range of functions, and (iii) multiplie sensors and actuators, storing and analysis of data, and network compatibility.

2.2.2 IoT

According to Ref. [1], the IoT and the IoS are what is driving the fourth industrial revolution as "The Internet of Things and Services makes it possible to create networks incorporating the entire manufacturing process that converts factories into a smart environment" [1]. As mentioned, the term IoT is sometimes used for the fourth industrial revolution. Here, however, it is viewed as one of the four key components of Industry 4.0, as identified by Hermann et al. [5]. By the introduction of the Internet protocol IPv6, there are now enough available addresses to uniquely identify and network resources, information, objects and people, creating the IoT and IoS [1].

Hermann et al. [5] defined the IoT as a network in which CPS cooperated with each other through unique addressing schemas. Slack et al. [13] described it as a combination of RFID chips, sensors and Internet protocols that allowed networking of the location and state of physical objects. As "things" and "objects" can be understood as CPS [5], the IoT and CPS are closely linked components of Industry 4.0. Future internet technology will enhance the performance of CPS [14]. The possibility to give a unique identification to every physical object will enable objects to be networked in the IoT and tracked, which makes the object an information carrier [14].

Slack et al. [13] further elaborated on the IoT's implications for operations management. The IoT will enable linking and networking of data from products, equipment and environment, enhancing information and enabling more sophisticated analysis [13]. Specifically, Slack et al. [13] addressed the knowledge of where things were, what was happening and what to do in an operations management context, as such knowledge could provide useful decision support. The IoT will enable gathering of this knowledge. Moreover, Slack et al. [13] emphasized that the IoT would enhance monitoring and data collection, improving process control significantly within a production facility.

2.2.3 Smart factory

Smart factory is the third component of Industry 4.0, as described by Hermann et al. [5], which defined it as a factory where CPS communicated over the IoT, assisting humans and machines in task execution. It enabled the collection, distribution and access of manufacturing relevant information in real-time [15]. Radziwon et al. [16] gave a more comprehensive definition of the term, saying: "A smart factory is a manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising on a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity. This special solution could on the one hand be related to automation, understood as a combination of software, hardware and/or mechanics, which should lead to optimization of manufacturing resulting in reduction of unnecessary labour and waste of resource. On the other hand, it could be seen in a perspective of collaboration between different industrial and nonindustrial partners, where the smartness comes from forming a dynamic organization." This last definition gives a more general view on the smart factory concept, where the word "smart" characterizes objects that are enhanced by additional features increasing its abilities. Although the definition does not explicitly say anything about IoT or CPS, the words “software”, “hardware” and “mechanics” are included, making the definition relatable to the other components of Industry 4.0 described earlier.

Digital factory is also used when describing the smart factory concept in relation to Industry 4.0 [4]. Yoon et al. [17] used the term “smart factory” interchangeably with “ubiquitous factory”, and defined it as “a factory system in which autonomous and sustainable production takes place by gathering, exchanging and using information transparently anywhere, anytime with networked interaction between man, machine, materials and systems, based on ubiquitous technology and manufacturing technology”. Smart factory can thus be considered a concept within the scope of Industry 4.0. Based on the preceding descriptions and definitions one can say that the smart factory is a factory where the other components of Industry 4.0 are combined and put in the context of production.

Having described the main features and key components of Industry 4.0, the next section will concern how these can be related to manufacturing logistics.

3 Industry 4.0 applications for manufacturing logistics

Through literature study, various applications of Industry 4.0 technologies in manufacturing logistics have been identified and placed in four groups, which are described in the following paragraphs.

3.1 Decision support and decision-making

New technology within Industry 4.0 has the potential to greatly enhance decision support and provide more automated decision-making. The new possibilities to collect and analyze data from products and processes can effectively give great benefits for manufacturing logistics, as managers can base decisions on what is actually happening on the shop floor of a production facility. Moreover, this can allow automating decision-making, compared to traditional ERP systems, which traditionally only provides decision support. Industry 4.0 technologies also promise the introduction of artificial intelligence and augmented and virtual reality in manufacturing, providing a new way of decision support and decision-making.

3.1.1 Artificial intelligence

The application of artificial intelligence to production and logistics is seen as a natural step, and can assist in creating systems that make decisions and carry out actions based on the current environment [18]. Within the context of Industry 4.0, massive amounts of data can be gathered where equipments and products will be able to act alone without the intervention of humans. Applications of artificial intelligence in smart factories which have had a large impact on both productivity and quality of resulting products have been demonstrated [19].

3.1.2 Big data analytics

The collection and analysis of production relevant data is a key enabler of efficient decision-making [13]. Collecting and analyzing information enables managers to base decisions on evidence rather than intuition [20]. With the ability to make products information carriers and the possibility for tracking and identifying products it will be possible to use this information for decision support and controlling production [13]. Within the Industry 4.0 concept the collection and analysis of data is often referred to as big data [1]. APICS defines big data as “A collection of data and technology that accesses, integrates, and reports all available data by filtering, correlating, and reporting insights not attainable with past data technologies”. Big data analytics is differentiated from traditional analytics in the way that the data processed are now available in higher volumes, with higher velocities and in more varieties than before [20]. Big data has the potential to improve demand forecasting, supply chain planning and other areas of production [21].

3.1.3 Augmented and virtual reality

Augmented reality (AR) systems can be used to assist in logistics, manufacturing, maintenance and training within an industrial context [22, 23]. The use of augmented reality combines information with the physical world to assist workers. Within logistics, pick-by-vision is a promising concept where AR technologies can enable fast, effective picking of parts and products. Work instructions for manufacturing and assembly operations can be given directly to workers through AR technologies [24]. These technologies show promise for assisting workers through integration of information into the working environment, reducing the cognitive load on workers and enabling better performance of various operations within logistics and manufacturing.

3.2 Identification and interconnectivity

The identification of objects and the interconnectivity available in the future factory essentially is what makes up the IoT. Automated identification technology has been used industrially for a long time [25]. Now, however, by network technology together with Auto ID technology, one is able to network information about products in a supply chain, and within a production facility [13], creating the IoT, where all products, equipments and other objects within a facility can be connected. The possibility to uniquely identify products, equip them with sensors when delivered to the customer, and utilization of networking technology, can pave the way for new business models where servitization is more prominent. Although this is outside the scope of this paper, it is important to keep in mind the vast possibilities concerning identification and interconnectivity.

3.2.1 Sensors

The smart factory is equipped with sensors [4]. They are a vital part of a CPS, as they enable data acquisition from machines, equipment, etc., and eventually creating self-aware and self-configuring manufacturing systems [12]. Sensor and actuator systems in the manufacturing equipment are enablers of acquiring real-time information on specific changes of the product, humans or processes in a facility [9].

3.2.2 Auto ID

"Automated identification involves the automated extraction of the identity of an object" [25]. By enabling accurate and timely information about a specific item to be stored, retrieved and communicated, this information can be used to assist in automated decision-making and control functions relevant to that item. Identification technology has been developing very fast, seeing significant drops in the price of tags, equipment and infrastructure [26]. Radio frequency identification (RFID) is a type of Auto ID technology where radio frequency communication is used to identify and track objects attached with RFID tags [27]. It is considered as an enabler of the IoT within the Industry 4.0 concept [5].

3.2.3 Networking technology

Connecting different objects via a network allows them to interact and cooperate with each other [5, 28, 29]. Objects can include products, mobile phones, machines and other units. Having products and materials constantly connected to the network can give a complete overview of product flow, which gives the ability to work with lower safety stocks and react more quickly to changes in the market. Today's networking technology also contributes to improving transport planning of finished goods with a supply chain by giving access to real-time status of all products in transport.

3.3 Seamless information flow

The factory of the future is digitalized with a high level of integration between the various subsystems, and it will be characterized by a seamless flow of information [6, 15]. A highly digitalized and vertically integrated factory will allow decision to be made based on real-time information, improving the activities of production planning and control.

3.3.1 Real-time planning and control

Access to real-time information allows for continuous and real-time planning and control of manufacturing operations [13]. Moving towards real-time control requires new conceptual models for planning and control. Real-time control is today applied on machine and production line level. However, at planning levels, including scheduling within the MES systems, existing concepts are based on cyclic data processing and re-planning. Industry 4.0 technologies have the potential of enabling real-time planning and control of all planning activities.

3.3.2 Integration of IT systems

Vertical integration is one main feature of Industry 4.0 [1], thus a vertical integration from the shop floor, up through different sub-systems and to the ERP system will give a holistic and integrated management of information, which can improve manufacturing logistics. Integration of IT systems and digitalization of production in the context of manufacturing logistics will mean that the tasks required for PPC and directing the flow of materials through the factory is performed with the support of IT systems. This will first require that the required systems are implemented, henceforth that the systems are utilized. The complete integration for real-time production control will also require an Auto ID enabled shop floor, as presented by Arica and Powell [30]. The integration of IT systems is necessary to fully achieve the potential benefits of Auto ID technology [30]. Real-time control of production through a RFID enabled shop floor requires that the information from the identification of objects are transmitted to the higher level IT system, whether it is an MES system or an ERP system.

3.3.3 Cloud manufacturing

Cloud computing is essentially "on-demand" IT-service [31, 32]. An extension of this into manufacturing allows for the transition to service-based manufacturing, known as cloud manufacturing (CMfg) [33]. The manufacturing resources and capabilities of companies can be linked to via cloud computing to potential customers of manufacturing services. The system can analyze the requirements and propose a service package, ranging from product design, manufacturing, testing and other manufacturing capabilities from the product life cycle. This connection between all manufacturing resources in a network, and the specific requirements of the customers, gives the ability to better utilize all the resources to give the desired output. Both the external and internal logistics can be optimized based on the requirements in manufacturing resources and capabilities.

3.4 Automation, robots and new production technology

Further automation, utilization of robots as well as emerging production technologies, can have great implications for future production processes, giving the fourth category, automation, robots and new production technology. Automation can be considered as one of the main trends and expected developments within the Industry 4.0 concept [9]. One aspect of automation relates to manufacturing equipment, which will be characterized by the application of highly automated machine tools and robots [9].

3.4.1 Industrial robots

The cost of industrial robots is quickly decreasing, and the amount of robots utilized in industrial production will continue to increase [34]. Furthermore, as the cost is decreasing, their abilities are increasing, making them more autonomous, flexible and cooperative [35]. Industrial robots have traditionally required a precisely defined environment, with pre-planning and programming of their movements, but technological developments within Industry 4.0 are now changing this [34]. Industry 4.0 will also give developments in how humans are integrated in the production activities. Stock and Seliger [9] outlined a development towards a production situation where robots and human workers were highly integrated and working collaboratively on joint tasks. Human-robot collaboration on the shop floor can be a measure for increasing technological support for operators in production environment where there are still significant proportions of manual operations.

3.4.2 3D printing

Additive manufacturing technology as 3D printing can be an enabler of more individualized production, which has been identified as one of the research streams within Industry 4.0 [7]. Additive manufacturing method's benefits over conventional manufacturing methods include batch reduction feasibility and design customization [36], which are relevant within the scope of Industry 4.0. Especially, supply chains where production of spare parts is a key part of the business due to high-level after-sales service are expected to benefit from effective use of additive manufacturing technologies [37].

3.4.3 Automatic guided vehicles

Automation and utilization of robots will also be of relevance in other areas apart from the production processes. Transportation, line feeding and material handling within a facility can also be exposed for more automated and robotized solutions. One example is automatic guided vehicle (AGV) systems for transporting material through a factory. Such systems are common in industry, although the aspect of autonomy makes such systems relevant in the Industry 4.0 context. Embracing technological developments such as autonomous and automatic systems for transportation and material handling can greatly benefit a company's internal logistics.

4 Implications of the production environment

The production environment can be described as the environment in which a production company operates. Thus, it concerns both external and internal factors. An important factor for describing a production environment is the customer order decoupling point (CODP). That is the point in the value creation process where a product is matched with an actual customer order. The placement of the CODP determines whether a company is make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO) or engineer-to-order (ETO). However, several other factors need to be considered when describing a company's production environment. The topics of production environments have been widely described and studied [2, 38–41], and the production environment is often described in terms of specific variables or characteristic features. To structure the variables, they were by Olhager and Rudberg [39] grouped in three categories: product related, market related and manufacturing process related. Jonsson and Mattsson [2] and Schönsleben [40] did a similar grouping of the environmental variables.

The implications of the production environment for the fit of planning methods and the design and selection of production planning and control systems have been widely studied, and the applicability of PPC methods have been found to differ between production environments [2]. There is no one-size that fits all approach to PPC, thus the characteristic features describing the production environment must be considered when designing the PPC system [2]. With the environmental variables' great impact on PPC, and thus companies' manufacturing logistics, this topic will be of high relevance and within the Industry 4.0 context.

A more general characteristic often used to describe production environment is the degree of repetitiveness of production [3]. According to Ptak and Schragenheim [42], a repetitive production company produced high volumes in low variety and competed in the market based on price and/or lead time. Typical manufacturing strategies for such producers are made to stock, configure to order or assemble to order [42]. Repetitive production is repeated production of the same discrete products or families of products, which minimizes setups, inventory, and production lead time [43]. High volumes and low varieties mainly characterize repetitive produced products. Moreover, the bills of materials (BOMs) have typically few levels, and product routings are fixed and reliable [42]. In less repetitive environments, like the job shop environment, products are produced in several varieties, and product routings may vary [42]. This causes increased complexity in the flow of materials and for PPC and manufacturing logistics in general. Ptak and Schragenheim [42] further argued for the importance of different approaches to PPC for these two general types of production environments. Stevenson et al. [44] and Fernandes and Godinho [45] conducted literature review to investigate the applicability of different PPC systems in environments of varying levels repetitiveness. The studies show that the applicability is highly dependent on the match with the production environment.

The multi-dimensional classification of production systems developed by MacCarthy and Fernandes [3] highlights how repetitiveness is dependent of characteristics, or variables, of the production system, or the production environment. By adding a variable describing the demand uncertainty or demand variation, all the categories (demand, product, and process) from Jonsson and Mattsson [2] are covered.

5 Methodology for case studies

To investigate how Industry 4.0 can improve manufacturing logistics, four case companies have been included in the study. The companies have been selected based on their stated goal of improving their internal flow of materials and general aim of improving their manufacturing logistics performance. Moreover, they represent a range of varieties of Norwegian manufacturing companies, where a key variable is the production environment the companies operate in. In a multiple case approach replication logic is supposed to reveal support for contrasting results for predictable reasons [46], in this case the production environment. The data on the case companies were obtained through two main approaches: a mapping of each company's production environment and a focus group survey.

The main information used for mapping the production environment stems from company visits with walk-around, workshops and meetings within the research project, which of the case companies are partners. The participants from the case companies in these meetings and workshops were mainly supply chain managers, production managers, and logistics managers. In addition, existing documentation of the case companies was made available for conducting the mapping. This information was then used to identify the characteristics of each case company.

To collect information from the case companies on their opinions and interpretations of Industry 4.0 and manufacturing logistics, a survey was made by following the general guidelines by Forza [47]. The survey contained questions concerning Industry 4.0 from a general perspective and from a manufacturing logistics perspective, covering the four categories discussed in Sect. 3. It was presented to the case companies in a workshop at NTNU, May 10, 2016. The workshop participants were representatives from the four case companies, as well as researchers, professors and PhD. candidates affiliated with one or more of the case companies through their research. Having been a part of the research project, all participants had insights in the case companies, and were able to contribute to answering the survey together with the case companies' representatives. This way of conducting a survey is similar to what is termed "focus groups" by Kitzinger [48]. Focus groups capitalize on communication between research participants in order to generate data, by taking a form of group interview [48]. Kitzinger [48] stated that such a group process could aid in clarifying and exploring views that would be more difficult to access in a one to one interview. The focus group method is particularly relevant when the survey questions are open ended, and requires discussion to be answered [48]. This was the case for the majority of the questions in the survey. Despite this methodology's advantages, it is not as well suited for covering the depth of a particular issue. Although that was not the intention of this study, it must be noted that more in-depth and detailed studies on the topic should include different or additional research methodologies. The group interview format may cause the discussions to go off topic, which may leave survey questions not fully answered.

The answering of the survey was organized by dividing the workshop participants into four groups, one for each case company. The representatives for the case companies were assigned to their respective group, while the other participants were randomly distributed among the groups. Each group was instructed to answer the survey jointly, where one answer was mutually agreed upon for each question. This reflects the group's interpretation and opinion as a whole. However, it is noted that the data obtained from this survey result in only one qualitative answer from each company.

6 Case studies

This section will introduce the four case companies as well as the key findings from the mapping, analysis and survey results. For all the companies the analysis will refer to the categories presented in Sect. 3.

6.1 Kleven

Kleven Maritime AS includes the two shipyards Kleven shipyard and Myklebust shipyard, both located on the west coast of Norway. Ship building at Kleven Maritime AS (from now Kleven) includes platform supply vessels, construction vessels, seismic vessels, and anchor-handling vessels.

Production at Kleven is characterized by ETO production. Ships are designed and engineered in close collaboration with the customer, allowing a very high degree of customization. This also makes Kleven's production one-of-a-kind production [49], producing one-offs every time. Production of ships requires a fixed position type of layout, where workers and materials are brought to the ship being produced. Compared to other types of layouts, the fixed position layout, which is common for shipbuilding and traditional ETO industries, is a factor for increasing the material flow complexity. This is also the case for Kleven.

Kleven focuses on modularization of products for achieving production efficiency. This means that ships are produced in modules, and then assembled into complete ships. The intention of this is to improve process control, production control and quality, and to reduce production lead times. Still, the typical throughput time is several months, up to 1–2 years. Naturally, the products produced by Kleven have a high product structure complexity, and a highly complex BOM with several levels, as well as a number of subassemblies. Consequently, only a small number of ships are produced each year.

Although Kleven is increasingly utilizing robots in the production, the manufacturing operations at Kleven are still mostly manual. The degree of automation and utilization of robots in the production is relatively low.

The survey response from Kleven indicates that the company has no specific opinion whether Industry 4.0 is a realistic goal for the company or not, and the company is only to a small extent investigating the specific opportunities of it. It is seen as neither a threat nor a possibility for the company in the future. Although, if pursued, it is to some extent expected to improve the manufacturing logistics of the company. The most important focus areas for the company today are standardizing products and components and reducing throughput times. Improving the flow of materials and applying better methods and principles for planning and control is somewhat important, while reducing work-in-process and inventories are not of any specific importance.

6.1.1 Decision support

To some extent, data collection from the production processes is used to analyze, monitor and control production today. An increase of this data collection, utilizing intelligent sensors and Auto ID technology, is expected to have some improving impact on manufacturing logistics, although it is not an important part of the company's strategy for the future.

6.1.2 Identification and interconnectivity

Implementing Auto ID technology such as RFID is not expected to improve the internal flow efficiency at Kleven's shipyard significantly. However, it is stated that Auto ID can be a means to increase integration with suppliers in the future.

6.1.3 Seamless information flow

Today, Kleven has implemented an ERP system. The current IT infrastructure is to some extent expected to be suited for transition to Industry 4.0. More integrated IT solutions are expected to have a great positive impact on the manufacturing logistics of the company. However, Kleven does not have any specific focus on using more of the functionality of the installed ERP system. On the other hand, there are clear future ambitions on making the yard operations more digitalized.

6.1.4 Automation, robots and new production technology

Kleven states that this category is the most relevant category for Industry 4.0 applications in manufacturing logistics. It is expected that 3D printing will be possible to implement in future operations. Moreover, over the last years, effort has been put into increasing the automation level and utilizing robots in production. For example some welding operations that previously were performed manually outside Norway now performed by robots at Kleven's shipyards in Norway. This is an enabler for maintaining production in Norway.

6.2 Brunvoll

Brunvoll AS develops and produces thruster systems for maneuvering and propulsion of several different types of advanced vessels. The company operates in a global market and is responsible for the whole thruster system. Business operations include design, production, sale and service. In addition to developing and producing new thruster systems, the after-sale market and service is an important part of the business for Brunvoll. This gives additional requirements in terms of spare parts production.

By producing thruster systems for advanced vessels, the business is highly dependent on the shipbuilding industry, which the main customers represent. Shipbuilding is a typical engineer-to-order industry [50], and this has implications on the production strategy and placement of the CODP for Brunvoll. Production is based on a combination of an ETO and MTO strategy, where customizations are allowed to a large extent. This gives a very high number of possible product variants. The shop floor layout is a combination of a fixed-position layout and cell layout, contributing to a high material flow complexity.

Brunvoll considers Industry 4.0 to be a realistic goal. However, the company has not put significant effort into investigating possible opportunities of it. From an overall perspective, it is by the company viewed as a slight opportunity for increasing competitiveness, although its impact on manufacturing logistics is only considered minor. The most important focus areas related to manufacturing logistics for Brunvoll are improving the flow of materials, reducing throughput time and inventories of raw materials and finished goods. Improving the methods and principles for planning and controlling production is part of this focus. Increasing the use of IT and integrating IT solutions are also issues to some extent, while standardization of products and components is considered less important.

6.2.1 Decision support

Data capture and analysis is only to a small extent used to monitor and control production at Brunvoll today. The logistics data that are collected include processing time, work-in-process, delivery time and reliability. The company to some extent agrees that improved data collection and analysis will improve the manufacturing logistics, and it is part of the production strategy for the coming years.

6.2.2 Identification and interconnectivity

Implementing Auto ID is not expected to be applicable for improving the internal material flow efficiency in the factory significantly. However, the company states that product identification and especially product tracking can be a measure to increase integration with customers. Brunvoll expects that this will enable better integration of the value chain.

6.2.3 Seamless information flow

Brunvoll has currently implemented an ERP system and a PLM system. In addition, implementing an MES system is under consideration. The company also expects that increased utilization and integration of IT systems will have major positive implications on manufacturing logistics, allowing more seamless flow of information. The company also states that there is a potential to utilize more of the functionality available in IT systems currently in place.

6.2.4 Automation, robots and new production technology

The use of additive manufacturing like 3D printing is highly relevant for Brunvoll as it is expected to be applicable to a large extent. Implementing such technology is also expected to contribute to reduced complexity related to manufacturing logistics to a large extent. Furthermore, the percentage of automated processes is expected to increase over the coming years, although not significantly.

6.3 Ekornes

Ekornes is a furniture production company, headquartered in Ikornnes on the west coast of Norway. They are positioned within the medium/high-end of furniture products, with the aim to be a leading actor and producer of branded goods within the home furniture industry, both in the national and international market. The company's most known product is the stressless reclining chair, but sofas, coffee tables, etc., are also part of the product portfolio.

Ekornes has a strong focus on allowing customization of products. However, the customization is typically in terms of skin type and color of chairs. On the other hand, it gives a large number of possible product variants. To be able to deliver their products to customers efficiently, the company has employed a combination of MTO and ATO production strategy. The effect in reality is that finalization of products is done after customer orders have been received. When a customer order is received, with the specific customization in terms of skin type and color, the skin is cut and sewed before the chair is assembled.

Production is organized in a functional shop floor layout, with different departments responsible for each of the main production stages. One of the characteristics of the functional layout type is a complex material flow, although if seen on a higher level all products follow the same overall route through the different departments for each of the main production stages as, e.g., the sewing department.

Ekornes' survey response indicates that Industry 4.0 is a realistic goal and an opportunity for the company, but they have only to a certain extent investigated the possibilities and opportunities of it. It is stated that Industry 4.0 on a general basis will improve the manufacturing logistics in the company to a large extent. Improving the efficiency of the material flow is a major focus area of Ekornes. Mainly this is to be achieved by reduced through put time and increasing IT utilization.

6.3.1 Decision support

Today, Ekornes collects and captures large amounts of logistics data. These include throughput time, processing time, work-in-process, and delivery reliability. However, such data are not used for analysis in a large extent. On the other hand, the company believes that using such data for analysis will improve the manufacturing logistics of the company significantly.

6.3.2 Identification and interconnectivity

The applicability of Auto ID technology like RFID in the production at Ekornes is considered high. However, the company states that implementation of Auto ID for product track and trace is believed to give only a moderate improvement in the flow efficiency of goods and material.

6.3.3 Seamless information flow

Ekornes has today an ERP and MES system installed. Although projects have been initiated to investigate the possibilities for implementing both APS and PLM systems. More integrated IT-systems can improve the manufacturing logistics to a large extent. In addition, there are functionalities of the current IT systems that are not utilized. However, the company has no specific focus related to increasing the IT system utilization.

6.3.4 Automation, robots and new production technology

Production technologies such as 3D printing are not expected to have any impact on the manufacturing logistics of Ekornes. On the other hand, the company expects that the level of automation and utilization of industrial robots will increase in the coming years.

6.4 Pipelife

Pipelife Norge AS is a part of the international Pipelife group. The group is headquartered in Austria, and is one of Europe's leading producers of plastic pipes. Pipelife Norge AS (from now Pipelife) is the Norwegian division of the group and produces plastic pipes in various areas, including water supply and sewage, heating ventilation and sanitation, cable protection, wiring and gas pipes.

Pipelife has an MTS production strategy, with highly standardized and repetitive production of pipes in large quantities. The CODP is placed at the finished goods inventory, from where products are picked and shipped. Thus, no customization is allowed. Product variety and complexity is low, with only 1–2 levels in the BOM. Pipelife aims for cost advantage through economies of scale in their mass production of plastic pipes, and production is organized in a highly automated product line shop floor layout, with changeover times and set-up times being major factors for planning and control. In this layout, the material flow is very streamlined, with a low material flow complexity.

Pipelife's response on the survey indicates that the company sees Industry 4.0 as a very realistic goal. The company is also largely investigating possible applications. Furthermore, Industry 4.0 in general is considered as a great opportunity for the company, and is expected to improve manufacturing logistics significantly. To achieve more efficient internal logistics, improving the flow of materials and increasing IT-utilization are the primary focus areas of Pipelife, together with reducing changeover times. Finding better methods and principles for planning and control and reducing inventories of raw materials and finished goods are also of a certain importance. Standardization of components, increasing flexibility and reducing work-in-process are less important focus areas.

6.4.1 Decision support

Production data is captured and analyzed at Pipelife today, and the company states that this will be increasingly important for improving manufacturing logistics in the future. Over the last three years, the quality of information available has improved significantly, but information is only to some extent accurate, timely and available for use. The sharing efficiency is also moderate. However, the company now has a strong focus on applying real-time capture and analysis of information for decision support and improving manufacturing logistics performance.

6.4.2 Identification and interconnectivity

Implementation of Auto ID is expected to be highly applicable for Pipelife, and it is expected to give significant improvements to manufacturing logistics performance. Auto ID technology such as RFID is expected to be applicable for improving production planning and control activities, purchasing and inventory control.

6.4.3 Seamless information flow

Pipelife has today implemented an ERP system and an MES system, and the current IT infrastructure is expected to be well suited for transition to Industry 4.0. Pipelife also states that more integrated IT solutions will have a positive impact on the manufacturing logistics of the company. On the other hand, Pipelife has to a large extent a focus on increasing the current IT utilization to apply more of the available functionality.

6.4.4 Automation, robots and new production technology

Production technologies such as 3D printing are not considered relevant for Pipelife. On the other hand, a large amount of the production processes are already automated. This, as well as the level of autonomy, is expected to increase over the next years.

7 Discussions of case study findings

The mapping of the case companies' characteristics revealed the difference in production environments of the four companies. Table 2 provides a comparison of the characteristics of them. In addition to the variables previously described in Table 1, this table includes the "Relative degree of repetitiveness". This is derived from the preceding variables and their total contribution to the repetitiveness. Each company has then been given a degree of repetitiveness, relative to the other companies. Kleven has the least repetitive production, while Pipelife has the most repetitive production.

Further, the applicability of the Industry 4.0 technologies described in Sect. 3 has been evaluated based on the focus group survey response. This is shown in Table 3.

As indicated by Slack et al. [13] and MacCarthy and Fernandes [3] the shop floor layout is an important source of creating complexity in a production environment, as it has an impact on the material flow complexity. Especially, in a fixed-position layout and a functional layout the material flows are not unidirectional. Shipbuilding is characterized by a fixed position layout, where materials, workers and production equipments have to be brought to the product being processed. In such a setting, monitoring and data collection of what is happening can be difficult and implementing real-time control to any extent can be more problematic than with layouts where the material flow is less complex, such as in the product line layout. On the other hand, one can argue that the need for identifying, tracking and tracing products is more valuable when the material flow is complex.

High product varieties can give implications for implementing Auto ID. It is expected that uniquely identifying a high number of product variants produced in low volumes is more difficult than uniquely identifying a low number of variants produced in high volumes. Auto ID is considered as a key enabler for real-time monitoring and control, which consequently can be difficult to implement for a company where product variety is high.

Although the sample analyzed only contains four companies, the results from the mapping and survey indicate that there is a relation between the repetitiveness of production, CODP placement and the companies' perceived Industry 4.0 applicability. Figure 1 shows the relationship

Table 1 Sources for repetitiveness in production (adapted from MacCarthy and Fernandes [3])

Variables	Description	Scale
CODP	Placement of the customer order decoupling point	ETO, MTO, ATO, MTS
Automation level	Amount of automated processes	Low, medium, high
Product structure complexity	Complexity of the average product structure	Low, medium, high
Level of customization	The level of customization allowed at customer order entry	Customized products, semi-customized products, standard products
Number of product variants	The number of products offered to customers	Low, medium, high
Layout	Organization of the facility shop floor	Fixed position layout, functional layout, group layout, product layout
Material flow complexity	The complexity of the flow of material through the factory	High, medium, low
Demand variation	The variation and uncertainty in customer demand	High, medium, low

Table 2 Classification of case companies based on repetitiveness in production

Variables	Kleven	Brunvoll	Ekornes	Pipelife
CODP	ETO	MTO	ATO	MTS
Automation level	Low	Low	Medium	High
Product structure complexity	High	High	Medium	Low
Level of customization	Customized	Customized	Semi-customized	Standard
Number of products	High	High	Medium	Low
Layout	Fixed position layout	Fixed position and cell layout	Functional layout	Product line layout
Material flow complexity	High	High	Medium	Low
Demand variation	High	High	Medium	Low
Relative degree of repetitiveness (from 1 to 4)	1	2	3	4

Table 3 Applicability of Industry 4.0 technologies in case companies

Industry 4.0 technologies	Kleven	Brunvoll	Ekornes	Pipelife
Artificial intelligence	Low	Low	Medium	High
Big data analytics	Medium	Medium	High	High
Augmented and virtual reality	High	High	Medium	Medium
Sensors	Medium	Medium	High	High
Auto ID	Low	Medium	Medium	High
Networking technology	Low	Medium	High	High
Real-time control	Medium	Medium	High	High
Integration of IT systems	Medium	Medium	High	High
Cloud computing	Medium	Medium	Medium	Medium
Industrial robots	Medium	Medium	High	High
3D printing	High	High	Low	Low
Automatic guided vehicles	Low	Low	High	High

Applicability has been evaluated in terms of two factors; the ease of implementation and the potential positive impact on manufacturing logistics performance

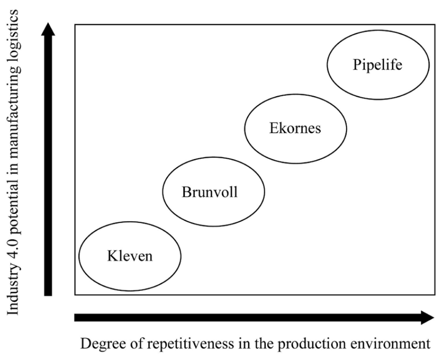

Fig. 1 Relationship between repetitiveness in production and perceived potential of applying Industry 4.0 technologies

between repetitiveness in production of the four case companies and the companies' perceived potential of applying Industry 4.0 technologies in manufacturing logistics. Of the four case companies included, Pipelife, characterized by a product line layout and MTS strategy, as well as low complexity in product structure and material flow, has the highest level of production repetitiveness. Pipelife is also the company that sees the highest potential for approaching and benefitting from Industry 4.0 and is most active in pursuing it. They see very high potential benefits from implementing Industry 4.0 technologies related to identification of products and interconnectivity to improve manufacturing logistics. In comparison, Ekornes and Brunvoll have lower levels of production repetitiveness, and ATO/MTO and MTO/ETO strategies, respectively. These two companies state the potential benefits of Industry 4.0 to be medium/high, and are not exploring the specific possibilities of Industry 4.0 in the same way as Pipelife. Lastly, Kleven is the most ETO-oriented company of the four, with the lowest level of production repetitiveness. Moreover, Kleven see less potential benefits from Industry 4.0 than the other companies in this study, and has the longest way to go to reach an Industry 4.0 level of production.

While the degree of repetitiveness is a critical factor for the choice of PPC system [3], and the choice of planning methods is dependent on the production environment [2], this study further indicates that the degree of repetitiveness in the production environment also affects the applicability of Industry 4.0. Characteristics of the production environment that cause increased complexity of the manufacturing logistics processes are expected to reduce, or at least imply on, the applicability of Industry 4.0 technologies. Thus, the differences in production environment call for different approaches to Industry 4.0, and conducting analyses of the production environment is a prerequisite before Industry 4.0 can be applied to manufacturing logistics. The mapping of the case companies' production environment, the survey results and the evaluation of the applicability of Industry 4.0 technologies have been used to develop a proposition suggesting that: There is a relationship between the applicability of Industry 4.0 technologies and the degree of repetitiveness in the production environment, and the applicability is higher in more repetitive production environments.

There are several aspects of the repetitive production environment that positively affects Industry 4.0 applicability. The low complexity of material flows, layout, and product structures in the repetitive production environment ease production control and monitoring. Thus, collecting data may be more convenient, giving both higher volumes and quality of production data. Industry 4.0 applications for data collection and analysis are thus easier to implement. In the process industry and the fast moving consumer goods industry, which are examples of industries with highly repetitive production, the level of instrumentation and the use of sensors for monitoring production are high. These industries typically have rigid production systems, with a high level of automation. As Industry 4.0 goes beyond the automation of production processes, the repetitive production environments are closer to the Industry 4.0 vision than environments characterized by a high amount of manual processes. All these aspects facilitates the transition to Industry 4.0 as described in Ref. [1].

Nevertheless, although the applicability of Industry 4.0 may be higher in repetitive production environments, the potential positive impact of Industry 4.0 applications may be equal, and possibly even higher, for the most non-repetitive production environments. The application of Industry 4.0 in non-repetitive production environments, typical for ETO and one-of-a-kind production, will thus be a highly relevant research topic for the coming years.

8 Conclusions, limitations and further research

This paper has discussed and presented a proposition regarding the fit of Industry 4.0 applications for manufacturing logistics in different production environments. The samples of case companies investigated in this study indicate that companies with low degree of production repetitiveness, high material flow complexity and high degree of ETO production are least suited for a transition to Industry 4.0 in terms of manufacturing logistics. In addition, these companies seem to be less enthusiastic of Industry 4.0. Companies with a higher degree of production repetitiveness, lower material flow complexity and lower degree of ETO production seem, in comparison, to be less challenged by the production environment. Moreover, they are more actively investigating the possibilities Industry 4.0 technologies can offer.

A general roadmap or set of guidelines for moving towards Industry 4.0 has not been identified in this study. Moreover, the findings from the case studies and analysis of the survey suggest that a roadmap for Industry 4.0 will be dependent on the characteristics of the production environment of each specific company. Especially the characteristics of the production environment that affect the repetitiveness of production will have implications on the applicability of Industry 4.0 in the context of manufacturing logistics. Hence, there is no "one-size fits all" approach when it comes to Industry 4.0. A company specific or industry specific approach seems necessary to reap the potential opportunities and benefits from Industry 4.0.

Conducting a study on more than one case company limits the level of detail of the mapping and analysis of the case companies. This is a limitation to the study. Moreover, with a scope aiming at manufacturing logistics, several other aspects related to Industry 4.0 have been neglected.

Further research should include more detailed investigations of how Industry 4.0 technologies can be applied in manufacturing logistics and where in the logistics system each technology application is most relevant. Moreover, a similar, larger scale survey should be conducted to further investigate the relationship between production environments and the potential applications of the Industry 4.0 technologies. Research is also needed to investigate how manufacturing companies characterized by a non-repetitive production can apply Industry 4.0 technologies. Especially, there is a need to investigate if one-of-a-kind manufacturing also can benefit from Industry 4.0 applications, as this study shows that it may be challenging due to such companies' low degree of repetitiveness. More specifically addressing the characteristics of the production environment that affects the repetitiveness of production, and how each of them affects applicability of industry 4.0 applications, may also be a topic for future research.

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Paper 5

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Paper 6

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Digitalized Manufacturing Logistics in Engineer-to-Order Operations

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Abstract. The high complexity in Engineer-To-Order (ETO) operations causes major challenges for manufacturing logistics, especially in complex ETO, i.e. one-of-a-kind production. Increased digitalization of manufacturing logistics processes and activities can facilitate more efficient coordination of the material and information flows for manufacturing operations in general. However, it is not clear how to do this in the ETO environment, where products are highly customized and production is non-repetitive. This paper aims to investigate the challenges related to manufacturing logistics in ETO and how digital technologies can be applied to address them. Through a case study of a Norwegian shipyard, four main challenges related to manufacturing logistics are identified. Further, by reviewing recent literature on ETO and digitalization, the paper identifies specific applications of digital technologies in ETO manufacturing. Finally, by linking manufacturing logistics challenges to digitalization, the paper suggests four main features of digitalized manufacturing logistics in ETO: (i) seamless, digitalized information flow, (ii) identification and interconnectivity, (iii) digitalized operator support, and (iv) automated and autonomous material flow. Thus, the paper provides valuable insights into how ETO companies can move towards digitalized manufacturing logistics.

Keywords: Engineer-to-Order · Digitalization · Manufacturing logistics

1 Introduction

The need for coordination of material and information flows in ETO operations is significant [1] and tailored approaches are required for an effective and efficient management of manufacturing operations [2]. Several studies have been aimed at addressing the challenges related to manufacturing logistics in different ETO cases, however, the aspect of digitalization has not yet been sufficiently addressed in this type of manufacturing environment [3].

The new, digital technologies within Industry 4.0 has the potential to change the manufacturing industry by enabling new and more efficient processes. Concepts and developments such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), augmented reality, artificial intelligence and big data analytics are expected to lead to a paradigm shift in industrial manufacturing [4]. Digitalization emerges as a way of managing complexity, and is introduced as one of the main areas for future research in

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complex ETO manufacturing [3]. With the high complexity in these manufacturing environments, there is a need to investigate how digitalization can improve manufacturing logistics performance. Therefore, this paper aims to identify how digital technologies can be applied in order to address the challenges in ETO manufacturing logistics.

The remainder of this paper is structured as follows. Section 2 presents and describes the characteristics of ETO manufacturing logistics. Thereafter, a case study serves to identify specific manufacturing logistics challenges. Applications of digital technologies in ETO is then identified through reviewing literature, before digitalization and manufacturing logistics challenges are linked in Sect. 5. The paper ends with the conclusions, limitations and further research in Sect. 6.

2 The Characteristics of Complex ETO Manufacturing

Manufacturing logistics concerns the coordination of the operations related to the flow of materials through the manufacturing departments up to the production of the end product [5]. Achieving cost-efficient manufacturing logistics in ETO is challenging due to the characteristics of the manufacturing environment [6]. With the ETO approach the activities of design, engineering, as well as the actual production processes, are performed after an actual customer order has been received. The customer order decoupling point is located at the design stage, with actual customer orders driving the production [7]. The large degree of customization, the product structure complexity, and the overlapping of manufacturing and design activities are reasons for a very high complexity of the internal ETO supply chain [8].

The most complex type of ETO manufacturing, which is the main focus of this paper, is the production of one-of-a-kind products [9]. Producing unique products every time has major implications for the manufacturing logistics processes, such as production control, as it creates a dynamic, uncertain and complex manufacturing environment [10]. Table 1 presents the main characteristics of complex ETO manufacturing.

Table 1. Main characteristics of complex ETO manufacturing.

Product characteristics: • Big-sized, complex products with deep product structures [3, 11] • High level of customization [9] • High product variety and low volume on product level (one-of-a-kind products) [2, 9]
Process characteristics: • Manufacturing carried out as large projects in fixed position layouts [9] • Frequent changes [11] • Highly integrated and overlapping activities [12] • Focus on flexibility [11]
Market characteristics: • Customer order decupling point located at the design stage [7] • Fluctuations and uncertainty in mix and sales volume [10] • Uncertainty in product specifications [10]

3 Manufacturing Logistics Challenges in Complex ETO

To get empirical data on how the characteristics of ETO manufacturing are affecting manufacturing logistics, a case study of the Norwegian shipyard Ulstein Verft AS (UVE) was conducted. Case data was collected through semi-structured interviews, observations at the yard and background data on the company from several years of research collaboration. This section includes a brief description of the case company and its manufacturing logistics.

UVE is part of Ulstein Group ASA, a Norwegian industrial group with activities in ship design and shipbuilding. The group's main business consists of designing and building highly customer-specific vessels, typically advanced offshore vessels such as supply vessels, anchor-handling vessels, offshore construction vessels and seismic vessels, in close collaboration with the customers. In recent years, they have also started building expedition cruise ships, yachts and passenger ships, in addition to ships for the offshore wind industry and developing designs for fishing vessels. UVE is the shipyard responsible for outfitting the ships delivered by the group. The hull production is carried out at a foreign yard, before the hull is towed to UVE in Ulsteinvik, Norway.

The production at UVE is a highly complex ETO production and the characteristics of the production environment at UVE bear a close resemblance to the ETO characteristics presented in Table 1. In general, there is a highly complex material and information flow related to outfitting activities at UVE, with non-repetitive and non-routine work processes. This is a result of the complex production of one-of-a-kind products, and a high uncertainty in process specifications. Moreover, processes are prone to disruptions due to changes occurring after the outfitting activities has started. This affects the planning, scheduling and sequencing of tasks, the supply of materials and the supporting documentations needed by operators to perform jobs. It is today challenging to achieve the tight integration of IT systems needed for efficient outfitting of the ships.

Paper-based documentation of product models and drawings are critical sources of information for operators in this type of manufacturing. Operators have a particularly important role in performing the outfitting activities at UVE, as standardization and automation of processes is difficult due to the non-repetitive type of work. Many operations are thus manual, including production processes, material handling and internal transportation of materials. Providing the required information to operators is further complicated when changes occur, as models and drawings then must be updated accordingly. Furthermore, it is difficult to have an overview of the yard from a manufacturing logistics perspective as operations are spread across a vast area. Materials, tools and equipment are thus geographically dispersed, and operators spend a considerable amount of time walking to collect or search for them.

From this, four main manufacturing logistics challenges at UVE are derived:

- IT system integration and sharing of up-to-date information
- Localization of materials, equipment and tools
- Complex and information demanding work for operators
- Manual material handling and irregular and disrupted flows.

4 Digital Technologies in ETO Manufacturing Logistics

Digital technologies emerge as promising means for managing complexity. While the technical developments of these technologies are rapidly advancing, applications in ETO still lags behind and requires research focus [3]. To have a structured overview of the available technologies and their features, eight technology groups were identified by integrating the technology clusters of smart manufacturing [13] and the nine advances in technology forming the foundation for Industry 4.0 [14]. This is shown in Table 2.

Table 2. Overview and description of digital technologies.

Tech. group	Description
Autonomous robots	Automatic Guided Vehicles (AGVs), Autonomous Mobile Robots (AMRs), and Collaborative robots (COBOTS) for material handling and performing logistics operations
Integration of IT systems	Horizontal and vertical integration of IT systems for production management (PLM, ERP, MES)
Internet of Things	Objects equipped with sensors and actuators, enabling storing and exchange of information through network technology
Cyber security	The secure and reliable protection of industrial production systems from cyber threats
Cloud manufacturing	Cloud-based solutions for sharing and exchange of data between systems, sites, and companies
Visual technology	The visual representation of an object, in the form of augmented reality (AR) through superimposing a computer-generated 3D image in the real world, creating a virtual reality (VR) or projecting 3D images as holograms
Data analytics	Transforming data into knowledge and actions within a manufacturing system. Big data for analysis of large sets of real-time data, artificial intelligence, machine learning and advanced simulations are all part of this group
Additive manufacturing	3D printing of objects layer by layer, based on 3D models or CAD files of the objects

Reviewing recent literature on ETO manufacturing and digitalization has identified a range of possible applications of these technologies. These are described in the following paragraphs of this section.

Several different IT systems are used at the different levels of today's manufacturing systems, but these are often not fully integrated [14]. However, the current technological developments in ICT increases the opportunity of achieving such an integration. Also in one-of-a-kind production, fully integrated, digitalized factories are possible through integrated sensor networks and supporting information systems [15]. Enhancing integration between modeling, scheduling and monitoring processes is particularly relevant for ETO [16]. Eventually, everything should be connected to a cloud-based solution and also taking the aspect of cyber security into account [17].

Digital technologies can be applied to assist operators to become smarter [18], and this is particularly relevant considering the high operator density in complex ETO. Visual technology such as Augmented reality [19] is one example of operator support that can enable schedules, product models and work instructions to be displayed on tablets or AR-glasses. Integration of such mobile devices with higher-level enterprise systems enables rapid sharing of updated information to the production floor. Such digital interfaces will also enable updating status of tasks through mobile devices, thus digitalizing progress reporting. Building Information Modeling (BIM) for information sharing through “BIM kiosks” is another means to provide operators with fast access to digital product models available from the PLM system [20].

Several papers have investigated the use of RFID for identification, localization and tracking [15, 19, 21]. Tracking and localization technology for automated data capturing of materials movement can enable real-time planning and control [15] such as real-time monitoring of assembly processes [22]. Furthermore, the integration of e.g. RFID, GPS and GIS technology with AR technology allows operators to get information on the location of materials, tools and equipment on mobile devices such as smart glasses or tablets. Drones is another possible application for localization purposes, as they can be utilized for inspection of the overall status of the shipyard [23]. Combining drones with 3D photography can then be used to provide 3D footage of the yard.

Although 3D printing mainly concerns production technology, such applications are also relevant for manufacturing logistics as it provides an ability for suppliers to send part designs to the yard for printing at the yard [23]. Moreover 3D printing can be used for printing of tools and equipment on the spot [23], hence it can reduce the time operators spend walking to acquire the tools and equipment necessary to perform a job.

Automated solutions for material handling are however the most promising developments to reduce time spent walking, waiting and searching. Automation of production processes, material handling and transportation of materials and equipment on the production floor has traditionally been difficult in complex ETO. However, with the increased flexibility of automated solutions today, the possibilities to automate such activities are increasing, exemplified by the use of AGVs, mobile robots, collaborative robots and automated material handling and feeding [24].

5 Features of Digitalized Manufacturing Logistics in ETO

Having identified various applications of digital technologies in ETO, it is now possible to link these to the manufacturing logistics challenges. Each of the identified challenges are here linked with a feature that can be provided by digital technologies.

The close integration between engineering and production in ETO manufacturing requires integrated IT systems for the efficient control and execution of manufacturing logistics activities. Moreover, with product changes occurring after production has started, it is necessary to provide operators with updated product drawings and models. Efficient information sharing is also required in the opposite direction, from shop floor to higher level IT systems, e.g. status and progress reporting from the production floor. With these challenges, there is a need for a *seamless, digitalized information flow*, where all subsystems at the various levels of the manufacturing system are integrated. Information should flow continuously from the production floor via MES system up to higher-level IT systems, such as the ERP system. This gives access to real-time information for planning and controlling operations.

The complexity of ETO products, with their deep bill of materials, makes it challenging to maintain an overview of all materials, equipment and tools necessary to perform operations. They are geographically dispersed across the facility, and workers often spend time searching for these assets, as well as walking over significant distances to acquire them. These challenges related to localization of materials, equipment and tools requires that *Identification and interconnectivity* is provided through digital technologies. It is now to a large extent possible to identify and interconnect objects in a facility through the utilization of new technology, and this will enable a highly integrated way of managing operations. Identification technology, networking technology and equipping products with sensors are keys to create a connected factory.

Operators in ETO manufacturing facilities such as UVE's shipyard must perform a range of highly complex, manual and non-routine tasks, as products are one-of-a-kind. Information about products, assemblies, processes etc. are therefore critical for the operators for them to be able to perform the scheduled tasks and activities. Digitalized manufacturing logistics should therefore include *digitalized operator support*. Human workers will still be important in a digitalized shipyard, and digital technologies should therefore be utilized to provide enhanced support for them, giving rapid and easy access to required and up-to-date information about the processes and activities.

With the manual material handling and irregular and disrupted material flow, there is a need for a more *Automated and autonomous material flow*. Products, components, tools, equipment and other objects can then be transported more efficiently, and with less human intervention. In manufacturing logistics, digital technologies can bring autonomy and automation to the physical flow of materials.

Figure 1 shows the manufacturing logistics challenges identified from the case study, and their corresponding required features of digitalized manufacturing logistics.

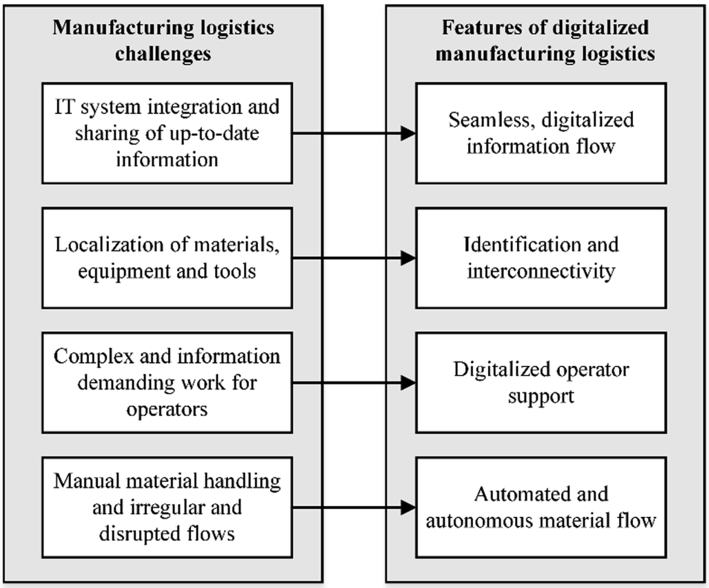

Fig. 1. ETO manufacturing logistic challenges and corresponding required features of a digitalized manufacturing logistics system.

6 Conclusions, Limitations and Further Research

This paper has identified a number of manufacturing logistics challenges in ETO manufacturing. It has further linked these to a set of required features of a digitalized manufacturing logistics system, outlining the needs that should be met by digital technologies. To be able to address the manufacturing logistics challenges in ETO there is a need for seamless, digitalized information flow, identification and interconnectivity, digitalized operator support, and automated and autonomous material flow. Digital technologies can enable these features, and there is a range of possible applications also in ETO. For digitalized manufacturing logistics in ETO several of the technologies should be applied and combined. Although there is still a lack of research on digitalization in ETO manufacturing [3], this paper identifies a range of digital technologies that has been applied or described conceptually for this type of manufacturing.

Further work related to this research will focus on developing more concrete descriptions of how the digital technologies can be implemented in the case company, and estimate the benefits in terms of relevant and measurable performance indicators such as time, cost, flexibility and quality. Future research should also include case studies of ETO manufacturers with similar characteristics as the case company in this paper, in order to generalize the findings.

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