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Doctoral thesis

Gabriele Hofinger Jünge

Lean Engineering Design:

Applying Lean Thinking to Engineer-To-Order (ETO) Operations.

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Norwegian University of Science and Technology
Thesis for the Degree of
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To Vegard, Erik and Linnea

“One of the challenges of research on lean (…) is discovering useful information, while avoiding the “one best way” conundrum. Assuming there is an optimum approach or one best way to implement a tool is antithetical to the continuous improvement underpinning lean thinking. As we continue to learn about lean (…), we have to accept that all answers are provisional and there is always a better way that someone will discover”, (Liker and Morgan, 2011, p. 27).

In this spirit, the contributions of this dissertation suggest a contemporary narrative of a “best way” for engineer-to-order (ETO) companies to follow on their journey of lean transformation. The findings of this research give us strong evidence that lean thinking can be a powerful way to significant improvement of engineering design in ETO operations.

Summary

Engineering design as part of engineer-to-order (ETO) operations allows companies to design and produce unique products that solve complex problems customized to individual needs. Companies, especially in high-cost countries such as Norway, use this form of customization as a key approach to outperforming competition from low-cost countries (Aakvik et al., 2014, Gosling et al., 2017, Hicks et al., 2001, Olhager, 2003).

ETO companies are typically characterized by a high level of product and process variation, high product complexity and deep product structures, and low production volumes. Each new order involves product design and development based on customer specifications, and hence products are typically highly customized (Olhager, 2003, Thomassen and Alfnes, 2017).

For companies following an ETO approach, engineering design is the process of evolutionary or incremental changes through which a series of relatively minor modifications to a product add up to substantial changes in the product's appearance, functionality, cost, and quality over time (Alderman et al., 2001). Such changes are less likely to emerge from the Research and Development (R&D) Department but are part of the day-to-day processes of applying scientific and engineering knowledge to technical problems and optimizing potential solutions within the requirements and constraints set by material, technological, legal, environmental, and human considerations (Pahl et al., 2007). More precisely, ETO companies conduct engineering design in three main phases: concept phase, basic design, and detailed engineering. However, engineering design is notorious for its inefficiency and waste generation (Ballard, 2000c). Arguably, its potential inefficient execution might negatively affect the coordination of all other important and intertwined ETO operations, such as sales, procurement, and production (Mello et al., 2015b), posing challenges concerning quality, resource utilization, lead time, and customer satisfaction (Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002).

Throughout the 20th century and until now, companies have adopted numerous methodologies to improve their operations. Lean thinking has arguably been the most

prominent of these methodologies (Found and Bicheno, 2016, Holweg, 2007). Lean thinking allows problems to surface and then uses the process of solving these problems to learn how to reduce the risk of their recurrence (Liker and Morgan, 2011). While lean thinking has a promising potential to improve ETO operations (Buer, 2020), the prevailing literature on lean thinking in ETO operations has mostly been applied to business areas such as production (cf. the opposite of engineering design), where it has proven its feasibility regarding continued improvements, waste reduction, and shortened lead times, among others (Netland and Powell, 2017, Powell and Van der Stoel, 2017, Strandhagen et al., 2018). While some aspects of lean thinking may be inappropriate for engineering design in ETO operations, it is worth developing a more nuanced discussion on what could, in principle, contribute to improvements.

However, when investigating the applicability of lean thinking in engineering design, Gosling et al. (2015) emphasize the problem of non-contextualization and the danger of creating the so-called "candidate solution" (using one solution from one scenario or context to another). In other words, while it seems easy to apply the principles of lean thinking to engineering design, without careful thought about translation and adaptation to context-specific scenarios, they may lead to unintended consequences for the organization attempting to utilize them. Against this backdrop, this research seeks to respond to this concern by incorporating reality with theory using multiple case studies and positing the following research aim of this dissertation:

Investigate how lean thinking needs to be adapted when applied to engineering design in order to improve its execution and its coordination with other ETO operations.

Therefore, research question 1 (RQ1) asked, "How can lean thinking be adapted to the execution of engineering design?" To begin with, through a single in-depth case study, the execution of engineering design in practice was examined, which allowed the identification of context-specific characteristics that challenged this process. In total, the study found eight real-world challenges that frequently led to an unleveled workflow. Unleveled workflow was undesirable as it resulted in overburdened engineering resources, as well as quality and lead-time deficiencies. Once the context to which lean thinking should be applied was analyzed, a literature review of lean practices resulted in a list of 20 practices that could potentially be adapted to engineering design.

Similarly, RQ2 asked, “How can lean thinking be adapted to the coordination of engineering design with other ETO operations (e.g., procurement and production)?” To begin with, an extensive multiple case study of 10 ETO companies mapped and analyzed current practices to obtain a thorough understanding of the context to which lean thinking would be applied. An extensive list of wastes was identified, which indicated how iterative engineering design caused wasteful activities while interacting with other interdependent and overlapping operations. By following a maturity model design method, nine lean enablers were identified as having the potential to be adapted to the coordination of ETO operations.

Finally, RQ3 asked, “How applicable is lean thinking to engineering design?” This question was addressed by evaluating the impact of the proposed lean practices on the execution of engineering design and the impact of lean enablers on the coordination of ETO operations.

Based on the findings that demonstrate the potentials of applying lean thinking to engineering design, this dissertation introduces *lean engineering design* as a concept of engineering products, services, and systems in a leaner way by adapting lean thinking to the context of ETO operations. In other words, *lean engineering design* proposes applying 20 lean practices when executing engineering design and applying nine lean enablers when coordinating engineering design with other ETO operations.

Through a rigorous design science research process that addresses relevant gaps in current theory, this PhD dissertation makes several theoretical and managerial contributions:

- analysis of the applicability of lean thinking to engineering design, as found in ETO operations;
- identification of real-world challenges concerning poor execution of engineering design;
- identification of 20 lean practices, aimed to improve the execution of engineering design;

- identification of key engineering design wastes;
- identification of nine lean enablers that enable the coordination of engineering design with other ETO operations;
- development of the concept of *lean engineering design*;
- analysis of how lean practices can be applied to improve the execution of engineering design by leveling workflow;
- analysis of how lean enablers can be applied to improve the coordination of engineering design with other ETO operations by reducing waste; and
- development of a maturity model as a management tool that guides managers on their path to lean transformation.

Overall, this dissertation should provide a better understanding and knowledge of how to adapt and apply lean thinking to engineering design, as found in ETO operations. As such, this dissertation aspires to support those who either study or manage project-based environments.

This dissertation has been carried out at the Norwegian University of Science and Technology (NTNU), Department for Mechanical and Industrial Engineering, with the financial support of the Norwegian Research Council. Associate professor Erlend Alfnes, as a main supervisor, and associated professor Marco Semini, as a co-supervisor, guided this research. The selected PhD committee composed of Professor Iris D. Tommelein, University of California, Berkeley and Professor Ralph Riedel, Westsächsische Hochschule Zwickau, University of Applied Science, has evaluated this dissertation.

Sammendrag

Engineering design som en del av Engineer-To-Order (ETO)-operasjoner lar selskaper designe og produsere unike produkter som løser komplekse problemer tilpasset individuelle behov. Bedrifter, spesielt i høykostland som Norge, bruker denne formen for tilpasning for å oppnå et konkurransefortrinn fra lavkostland (Aakvik et al., 2014, Gosling et al., 2017, Hicks et al., 2001, Olhager, 2003).

ETO-selskaper er vanligvis preget av høye produkt- og prosessvariasjoner, høy produktkompleksitet og komplekse produktstrukturer og lave produksjonsvolumer. Hver ordre innebærer ny produktdesign og utvikling basert på kundespesifikasjoner, og produktene er vanligvis sterkt tilpasset (Olhager, 2003, Thomassen og Alfnes, 2017).

For selskaper som følger en ETO-tilnærming, er engineering design-prosessen med evolusjonære eller inkrementelle endringer der en rekke relativt små modifikasjoner av et produkt gir betydelige endringer i produktets utseende, funksjonalitet, pris og kvalitet på produktet over tid (Alderman et al., 2001). Slike endringer kommer mindre sannsynlig fra forsknings- og utviklingsavdelingen (FoU), men er en del av de daglige prosessene hvor man anvender vitenskapelig og ingeniørkunnskap på tekniske problemer og optimalisere potensielle løsninger innenfor kravene og begrensningene satt av materiell, teknologisk, juridiske, miljømessige og menneskelige forhold (Pahl et al., 2007). ETO-selskaper gjennomfører engineering design i tre hovedfaser: konseptfase, grunnleggende design og detaljert prosjektering. Imidlertid er engineering design beryktet for sin ineffektivitet og sløsing (Ballard, 2000c). Den potensielle ineffektive utførelsen kan uten tvil påvirke koordineringen av andre involverte ETO-operasjoner som salg, innkjøp og produksjon (Mello et al., 2015a) som skaper utfordringer angående kvalitet, ressursutnyttelse, leveringstid og kundetilfredshet (Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002).

Gjennom de siste tiårene har selskaper tatt i bruk en rekke metoder for å forbedre operasjoner. Lean thinking har uten tvil vært den mest fremtredende av disse metodene (Found and Bicheno, 2016, Holweg, 2007). Lean thinking lar problemer dukke opp, og bruker deretter

prosessen med å løse disse problemene for å lære å redusere risikoen for å gjenta dem (Liker og Morgan, 2011). Selv om lean thinking har et lovende potensial for å forbedre ETO-operasjoner (Buer, 2020), har den rådende litteraturen om lean thinking i ETO-operasjoner stort sett blitt brukt på forretningsområder som produksjon (jf. motsatt av engineering design) der den har bevist sin gjennomførbarhet for eksempel kontinuerlig forbedringer, reduksjon av avfall og forkortelse av ledetider (Netland og Powell, 2017, Powell og Van der Stoel, 2017, Strandhagen et al., 2018). Selv om noen aspekter av lean thinking kan være upassende for engineering design i ETO-operasjoner, er det verdt å utvikle en mer nyansert diskusjon om hva som i prinsippet kan bidra til forbedringer.

Når vi undersøker anvendeligheten av lean thinking i engineering design, understreker imidlertid Gosling et al. (2015) problemet med ikke-kontekstualisering og fare for å lage den såkalte "kandidatløsningen" (ved å bruke en løsning fra et scenario eller kontekst til en annen). Med andre ord, selv om det virker lett å anvende prinsippene for lean thinking på engineering design, kan det føre til utilsiktede konsekvenser for organisasjonen som prøver å bruke dem uten nøye vurdering på oversettelse og tilpasning til kontekstspesifikke scenarier. Med dette som bakgrunn søker denne avhandlingen å svare på denne bekymringen ved å forene virkeligheten med teori ved hjelp av flere case-studier og å sette følgende forskningsmål for denne avhandlingen:

Å undersøke hvordan lean thinking må tilpasses når den brukes på engineering design for å forbedre utførelsen og koordineringen med andre ETO-operasjoner.

Tre forskningsspørsmål (RQ1-3) ble definert for å kunne adressere dette formålet. RQ1 undersøkte hvordan lean thinking kan tilpasses utførelsen av engineering design. En grundig casestudiet studerte utførelsen av engineering design i praksis som tillot identifisering av kontekstspesifikke egenskaper som utfordret denne prosessen. Totalt ble det funnet åtte utfordringer som ofte førte til en ujevn og ubalansert arbeidsflyt. En slik arbeidsflyt var uønsket da det resulterte i overbelastning av ingeniørressurser, kvalitet og økt ledetid. Når konteksten som lean thinking skulle brukes på var analysert, resulterte en litteraturgjennomgang av lean praksis i en liste over 20 praksiser som potensielt kan tilpasses engineering design.

Tilsvarende undersøkte RQ2 hvordan lean thinking kan tilpasses koordinering av engineering design med andre operasjoner, for eksempel innkjøp og produksjon. Til å begynne med kartla omfattende casestudier av 10 ETO-selskaper dagens praksis for å få en grundig forståelse av konteksten lean thinking vil bli brukt på. En betydelig liste over sløsing ble identifisert som ga ny kunnskap om hvordan iterativ engineering design forårsaket sløsing. Ved å følge en modenhetsmodell-designmetode ble det identifisert ni lean enablers som potensielt kan tilpasses koordinering av ETO-operasjoner.

Til slutt undersøkte RQ3 hvor anvendelig lean thinking er på engineering design ved å evaluere virkningen av den foreslåtte lean praksis på utførelsen av engineering design og effekten av lean enablers på koordineringen av ETO-operasjoner.

Basert på funnene som demonstrerte potensialene ved å bruke lean thinking på engineering design, introduserer denne avhandlingen begrepet *lean engineering design* som et konsept for å designe og konstruere produkter, tjenester og systemer på en lean måte ved å tilpasse lean thinking til konteksten av ETO-operasjoner. Med andre ord foreslår *lean engineering design* å anvende 20 lean praksis ved utførelse av engineering design og å bruke ni lean enablers når man koordinerer engineering design med andre ETO-operasjoner.

Studien ble gjennomført innenfor 'Design Science'-paradigmet som adresserte relevante hull i nåværende teori. Denne doktorgradsavhandlingen gir flere teoretiske og praktiske bidrag:
- Analyse av anvendbarheten av lean thinking for engineering design som finnes i ETO-operasjoner
- Identifisering av utfordringer for dårlig utførelse av engineering design
- Identifisering av sløsing innen engineering design
- Identifisering av 20 lean praksiser og demonstrasjon av hvordan de forbedrer utførelsen av engineering design ved å jevne ut arbeidsflyt

- Identifisering av ni lean enablers og demonstrasjon av hvordan de forbedrer koordineringen av ETO-operasjoner ved å redusere sløsing
- Utvikling av konseptet lean engineering design
- Utvikling av en modenhetsmodell som et styringsverktøy som veileder ledere på deres vei til lean transformasjon.

Totalt sett bør denne oppgaven gi en bedre forståelse og kunnskap om hvordan man kan tilpasse og anvende lean thinking på engineering design i ETO-operasjoner. Som sådan ønsker denne studien å støtte de som enten studerer eller administrerer prosjektbaserte miljøer.

Denne avhandlingen er utført ved Norges teknisk-naturvitenskapelige universitet (NTNU), Institutt for Maskin- og Industriteknikk, med økonomisk støtte fra Norges Forskningsråd. Førsteamanuensis Erlend Alfnes, som hovedveileder, og førsteamanuensis Marco Semini, som medveileder, har veiledet denne forskningen. Den utvalgte vurderingskomiteen sammensatt av professor Iris D. Tommelein, University of California, Berkeley og professor Ralph Riedel, Westsächsische Hochschule Zwickau, University of Applied Science, har evaluert denne avhandlingen.

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Finally, and most importantly, my family and friends, for the support and encouragement. My husband, Frode, for trying to understand and for making sacrifices to enable me to complete this dissertation. My children Vegard, Erik and Linnea that hopefully will forgive and understand one day.

Abbreviations

APM	Agile Project Management
APMS	Advances in Production Management System
BOK	Bodies of Knowledge
CEO	Chief Executive Officer
DSR	Design Science Research
EPC	Engineering, Procurement and Construction
ETO	Engineer-To-Order
EurOMA	European Operations Management Association
EVM	Earned Value Management
FEED	Front-End Engineering Design
FIFO	First-In-First-Out
GA	General Arrangement
GDP	Global Domestic Product
IGLC	International Group of Lean Construction
KPI	Key Performance Indicator
LPD	Lean Product Development
LPP	Lean Project Planning
LPPD	Lean Product and Process Development
LPS	Last Planner System
MAROFF	Maritime Activities and Offshore Operations
MIT	Massachusetts Institute of Technology
MM	Maturity Model
NTNU	Norwegian University of Science and Technology
OM	Operations Management
PDCA	Plan-Do-Check-Act
PhD	Philosophia Doctor
PM	Project Management
PMA	Performance Measurement and Management Association
PMBOK	Project Management Bodies of Knowledge
PPC	Percent Plan Complete
R&D	Research and Development
RQ	Research Question
SBCE	Set Based Concurrent Engineering
SMEs	Small and Medium-sized Enterprises
TPDS	Toyota Product Development System
TPS	Toyota Production System
VO	Variation Order

List of Appended Papers

Paper 1:

Jünge, G. H., Kjersem, K., Shlopak, M., Alfnes, E., Halse, L. L (2015). From First Planner to Last Planner: Applying a Capability Model to Measure the Maturity of the Planning Process in ETO. *Advances in Production Management Systems: Management Towards Sustainable Growth. 5-9 September 2015, Tokyo, Japan, pp. 240-247*

Gabriele H Jünge conceptualized the paper, collected and analyzed the data, and wrote the paper. Co-authors provided feedback and comments for revisions.

Paper 2:

Jünge, G. H., Alfnes, E., Kjersem, K, Andersen B. (2019). Lean project planning and control: empirical investigation of ETO projects. *International Journal of Managing Projects in Business*, 12, 1120-1145.

Gabriele H Jünge conceptualized the paper, collected and analyzed the data, and wrote the paper. Co-authors provided feedback and comments for revisions.

Paper 3:

Jünge, G. H., Alfnes, E., Nujen, B. B., Emblemsvåg, J., Kjersem, K. (2021). Understanding and eliminating waste in Engineer-to-order (ETO) projects: a multiple case study. *Production Planning and Control*, *7-17.*

Gabriele H Jünge conceptualized the paper, collected and analyzed the data, and wrote the paper. Bella B. Nujen, co-author, assisted in writing parts of the paper and provided feedback and comments for revisions. The remaining co-authors provided feedback and comments for revisions.

Paper 4:

Jünge, G. H., Nujen, B. B., Alfnes, E. (forthcoming). Lean practices assisting in overcoming unleveled workflow in engineering operations: A case study. *Engineering management journa*l (under review).

Gabriele H Jünge conceptualized the paper, collected and analyzed the data, and wrote the paper. Bella B. Nujen, co-author, assisted in writing parts of the paper and provided feedback and comments for revisions. The remaining co-authors provided feedback and comments for revisions.

Table of Contents

Part I

Main Report

1. Introduction

This chapter provides a general introduction to this PhD dissertation. It describes the motivation for studying engineering design in engineer-to-order (ETO) operations, the research problem, and the corresponding research questions (RQs). It also defines the research aim and this study's scope.

Companies, especially in high-cost countries such as Norway, use customization as a key approach to outperforming competition from low-cost countries. This customization is particularly manifested in offering unique solutions to individual customer and market requirements (Aakvik et al., 2014, Gosling et al., 2017, Hicks et al., 2001, Olhager, 2003). To allow such an ongoing customer involvement, companies apply an ETO approach where engineering design and production comply with customer requirements throughout the order fulfillment process (Olhager, 2003). The increased demand for customized products has generated a growing number of ETO companies that can typically be found in shipbuilding, oil and gas installations, and heavy equipment construction (Mello, 2015, Semini et al., 2018). In the USA alone, the number of ETO companies has increased by 20% per year, making ETO operations an interesting research subject (Grabenstetter and Usher, 2014).

However, various authors (Amaro et al., 1999, Bertrand and Munstlag, 1993, Braiden et al., 1993, Cannas and Gosling, 2021, Gosling and Naim, 2009, Little et al., 2000, Willner et al., 2016b) have described ETO operations as fundamentally different from those of mass production. In addition to traditional production, ETO operations require substantial efforts in sales, procurement, engineering design, and project management (PM) (Strandhagen et al., 2018). These operations consist of processes that are typically non-repetitive yet labor intensive and often require highly skilled employees (Powell et al., 2014).

Engineering design is inherent in all ETO operations and lies at the heart of customized value creation. However, engineering design is notorious for its inefficiency and waste generation (Ballard, 2000c), and its potential inefficient execution might negatively affect the coordination of all other important and intertwined business areas, such as sales, procurement, and production (Ballard, 2000b, Braiden et al., 1993, Emblemsvåg, 2020, Liker and Morgan, 2019, Oppenheim, 2004, Pahl et al., 2007, Reinertsen, 1997).

Due to a specific product's scope, complexity, and uniqueness, ETO operations are organized as projects, meaning that the core operations, including sales, engineering design, procurement, and production, are grouped as typical project-based environments (environments where activities are organized in projects). However, ETO operations vary, due to some typical characteristics (as explained in Chapter 2); consequently, extant literature points at the shortcomings of the traditional PM theory when applied to ETO operations (e.g., Emblemsvåg, 2014b, Laufer et al., 2015, Laufer and Tucker, 1987, Oehmen and Steuber, 2012).

Throughout the 20th century and until now, companies have adapted numerous methodologies to improve their operations. Lean thinking has arguably been the most prominent of these methodologies (Found and Bicheno, 2016, Holweg, 2007). This holistic management philosophy is credited for the extraordinary rise of Toyota as the most profitable and largest auto company in the world and is an established paradigm in manufacturing, administration, supply chain management, and product development (Oppenheim, 2011). Lean thinking allows problems to surface and then uses the process of solving these problems to learn how to reduce the risk of their recurrence (Liker and Morgan, 2011). While lean thinking offers the potential for significant reductions in cost and lead time, the transition to this approach is complex in practice (Ballard, 2017, Karlsson and Åhlström, 1996, Netland, 2016). More specifically, this transition requires rethinking of all involved operations, which has received limited scrutiny from scholars (Reinertsen, 2005), with a few important exceptions. However, these exceptions are largely limited to industries that produce either very large products, such as the aerospace industry (Oppenheim, 2011, Reinertsen, 2007), or a huge amount of products, such as the automotive industry (Oliver et al., 2007, Ward and Sobek II, 2007), or engage in onsite production, such as the construction industry (Ballard, 2000c). More importantly, the prevailing literature on lean thinking in ETO operations has mostly been applied to business areas, such as production (cf. the opposite of engineering design), where it has proven its feasibility regarding continued improvements, waste reduction, and shortened lead times (Netland and Powell, 2017, Powell and Van der Stoel, 2017, Strandhagen et al., 2018). While some aspects of lean thinking may be inappropriate for engineering design in ETO operations, it is worth developing a more nuanced discussion on what could, in principle, contribute to improvements.

In summary, it can be concluded that companies following an ETO approach need to handle several crucial issues in the years to come, which therefore deserve further research. Thus, this dissertation investigates the applicability of lean thinking and proposes the term *lean engineering design* based on the combination of three bodies of knowledge (BOK)—(1) ETO operations (Cannas and Gosling, 2021), (2) PM (PRINCE2, 2009, Institute, 2008), and (3) lean thinking (Womack and Jones, 1996, Womack et al., 1990)—which are presented in Chapter 2.

In this dissertation, the term *lean engineering design* is introduced because it posits that lean thinking—a concept derived from repetitive manufacturing—can equally be of value in the context where the overall system (e.g., the process of executing and coordinating engineering design) is designed and redesigned.

1.1. Research motivation

Engineering design is the approach that engineers use to identify and solve problems and includes both new product design and the incremental design of existing products to adjust to changes in marketing, manufacturing, functional deficiencies, and so on. Engineering design has been described and mapped out in many ways (Dixon, 1989, Penny, 1970, Ulrich and Seering, 2002, Wallace and Hales, 1987, Winner et al., 1988), including some common attributes: (1) Engineering design is a process (of problem solving, flexible enough to work in almost any situation where engineers learn important information about both the problem and possible solutions at each step of the process). (2) Engineering design is purposeful (beginning with an explicit goal). (3) Engineering design is *design under constraint* (solutions that include the most desired features and the fewest negative characteristics are chosen, within the limitations of the given scenario, including time, cost, and the physical limits of tools and materials). (4) Engineering design is systematic and iterative (including steps such as planning, modeling, testing, and improving design that can be repeated, although not always in the same order). (5) Engineering design is a collaborative process (often done in small teams that include people with different kinds of knowledge and experience. Engineering designers are continuously communicating with clients, team members, and others).

For companies following an ETO approach, engineering design is the process of evolutionary or incremental changes through which a series of relatively minor modifications to a product add up to substantial changes in the product's appearance, functionality, cost, and quality over time (Alderman et al., 2001). Such changes are less likely to emerge from the Research and Development (R&D) Department but are part of the day-to-day processes of applying scientific and engineering knowledge to technical problems and optimizing potential solutions within the requirements and constraints set by material, technological, legal, environmental, and human considerations (Pahl et al., 2007).

More precisely, in ETO operations, engineering design is conducted in three main phases: concept, basic design, and detailed engineering. First, the main concept is designed; this phase ranges from a few days to several years, depending on the market situation and the design's complexity. At some point, the contract is awarded (customer order), a project organization is formed, and the basic design starts. Typically, a project manager leads the project organization, comprising representatives of all operations, such as sales, engineering, procurement, and production. To keep lead times short, ETO operations follow a near-concurrent fashion (Emblemsvåg, 2014a). The idea of concurrence suggests the simultaneous involvement of all relevant operations throughout the project. Detailed engineering follows, including the creation of all drawings required for production.

Typical ETO operations include sales, PM, engineering design, procurement, and production, as shown in Figure 1. The length and the degree of overlap between engineering design and other ETO operations vary from project to project.

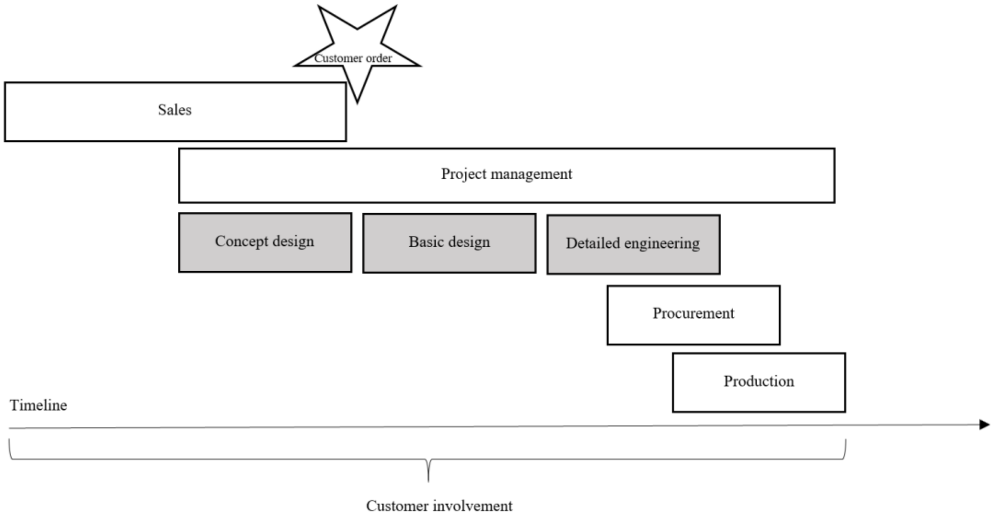


Figure 1. Three phases of engineering design in engineer-to-order (ETO) operations (from Paper 4)

To succeed with ETO operations, companies need to understand and adjust to changing customer requirements, as well as possess the ability to translate these requirements into solutions. An important notion here is that customers are willing to pay extra for this customization compared with typical manufacturing, where the product is defined in detail before production, and changes outside the scope of the initial design become impossible (Amaro et al., 1999, Bertrand and Munstlag, 1993, Braiden et al., 1993, Gosling and Naim, 2009, Hicks et al., 2001, Little et al., 2000, Willner et al., 2016b). In other words, the master data required to define the ETO product are not or even cannot be fully developed when the contract is signed (Emblemsvåg, 2020); rather, the data need to be developed iteratively, generating both value and waste.

Consequently, a product's requirements are broadly defined in the beginning of a project and evolve iteratively as the project proceeds. During this process, preliminary drawings are produced to improve the design and provide the customer with alternative solutions. When approved by the contracting parties and the regulatory bodies, the drawings can then be released as blueprints for production (Ulrich and Eppinger, 1999). However, before this can occur, information is passed back and forth several times before final approval, resulting in numerous engineering design hours that constitute a significant number of the total hours used for project delivery (Willner et al., 2016b). The number and duration of iterations are difficult to predict, posing challenges concerning quality, resource utilization, lead time, and customer satisfaction (Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002).

By the time a product is designed, 80% of the cost has been determined, which indicates that most of a product's total lifecycle cost is determined in the concept-design phase (Anderson, 2008). As such, engineering design activities are considered to have a high potential to strengthen a company's competitive advantage. Therefore, the efficient execution of engineering design (as defined in a leveled workflow that is balanced and uninterrupted) and the management of its impact on downstream activities (e.g., engineering design's and other business areas' interdependence) are important goals for ETO companies.

However, empirical studies reveal that organizations spend over 50% of their engineering design activities on non-value-adding activities, while the remaining 50% is split between value-adding and non-value-adding-but-necessary activities (e.g., (Ballard, 2000c, Bonnier et al., 2015, Freire and Alarcon, 2000). Thus, an interesting and important contribution to a better understanding of engineering design and how its execution can be managed efficiently is evidently needed.

The high degree of customization, the product structure complexity, and the overlapping of operations (e.g., concurrent execution of procurement, engineering design, and production) are the reasons behind coordination difficulties. Additionally, due to the scale of ETO operations, most of them involve a large number of participants; therefore, approximately 75% of a product's value is generated by involving suppliers and subcontractors (Dubois and Gadde, 2002). It means that the company that manages the contract executes only a small part of it, using the company's own employees and facilities. Thus, ETO operations challenge the coordination of engineering design with other involved ETO operations in all its aspects (c.f., PMBOK®). Although it is argued in extensive literature (e.g., (Albert et al., 2017, Andersen et al., 2007, Gosling and Naim, 2009, Hicks et al., 2001, Hussein, 2013, Liker and Lamb, 2000, Müller and Turner, 2005, Rolstadås et al., 2014, Willner et al., 2016b, Yamin and Sim, 2016) that planning and controlling constitute essential parts of coordinating multiple operations and are important drivers that can contribute to either success or failure in meeting the set objectives, few companies have well-functioning processes in place.

In line with the literature (cf. Adrodegari et al., 2015), it might be argued that the planning and control process as part of coordinating projects is one of the main areas for achieving a competitive advantage, leading to the following assumptions: Engineering design creates value by making decisions that allow the development of the ETO product. Those decisions are based on the knowledge, information, and experience available in the organizations managing the ETO operations. The coordination involved in how to gather, analyze, utilize, and reuse the knowledge, information, and experiences available is challenging and thus represents a gap in operations management (OM) research (Emblemsvåg, 2017, Nesensohn et al., 2014, Willner et al., 2016a).

To sum up, it can be argued that on one hand, there is a need to increase the efficiency of engineering design as it is notorious for being one of the major causes of unleveled and interrupted workflow, which additionally imposes negative implications for quality, costs, and delivery time. On the other hand, there is a need to rethink traditional PM when coordinating ETO operations. Considering the challenges and arguments outlined above, the next section presents the research problem and the RQs that assist in addressing it.

1.2. Research problem and research questions

Lean thinking has a promising potential to improve ETO operations (Buer, 2020). However, lean thinking in ETO operations has mostly been applied to production (cf. the opposite of typical engineering design), where it has proven its feasibility regarding continued improvements, waste reduction, and shortened lead times (Netland and Powell, 2017, Powell and Van der Stoel, 2017, Strandhagen et al., 2018), with a few but notable exceptions that explore its applicability to other non-production business operations (e.g., (Beauregard et al., 2011, Hoppmann et al., 2011, León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011, Nepal et al., 2011). The latter group of cited authors highlight some interesting results when advocating lean thinking as similarly applicable to and effective in non-physical and non-repetitive business operations as in more traditional production systems. While these are significant contributions, Gosling et al. (2015, pp. 203–204) emphasize the problem of non-contextualization and the danger of creating the so-called “candidate solution” (using one solution from one scenario or context to another). In other words, while it seems easy to apply the principles of lean thinking to engineering design, without careful thought to translation and adaptation to context-specific scenarios, they may lead to unintended consequences for the organization attempting to utilize them. Against this backdrop, this research seeks to respond to this concern by incorporating reality with theory using multiple and in-depth case studies and positing the following research problem:

There is a lack of understanding about how lean thinking can be applied to ETO operations to improve the execution of engineering design and its coordination with other ETO operations.

While lean thinking offers the potential for significant reductions in cost and lead time, an agreement on a set of guiding principles that enable the application of the lean philosophy in engineering design, as found in ETO operations, is far from established. Therefore, this PhD study investigates how lean thinking can be adapted and applied to the execution of engineering design and its coordination with other ETO operations. To attain the overall aim of this research in a comprehensive manner, three RQs are formulated.

RQ1. *How can lean thinking be adapted to the execution of engineering design?*

This first question is relevant as it guides the need to investigate how elements of lean thinking can be adapted to improve the execution of engineering design. To answer this question, the main drivers that hinder a leveled engineering design workflow are mapped, analyzed, and elaborated on to propose solutions on how companies and their managers can execute engineering design more efficiently by following a set of potential lean practices.

RQ2. *How can lean thinking be adapted to the coordination of engineering design with other ETO operations?*

This second question is relevant as it focuses on the need to identify how elements of lean thinking can be adapted to improve the coordination of engineering design with other ETO operations, such as procurement and production. To answer this question, key wastes in engineering design are mapped, analyzed, and elaborated on to propose solutions on how companies and their managers can coordinate engineering design with other ETO operations more efficiently by following a set of lean enablers.

RQ3. *How applicable is lean thinking to engineering design?*

Building on the findings about RQ1 and RQ2, the findings about RQ3 will contribute to the validation of the suggested artifacts (lean practices and lean enablers) of the design science research process used in this dissertation (which is thoroughly introduced in Chapter 3). This is done by investigating how lean thinking can level engineering design workflow and how it can minimize waste by improving the coordination of ETO operations. The findings will result in suggestions for best practices, which are important contributions.

The synthesis of the findings about all three questions is intended to contribute to the development of the concept of *lean engineering design* that enhances the execution of engineering design and its coordination with other ETO operations through elements of lean thinking.

Thus, by focusing on non-physical business operations, such as engineering design, which is the main topic addressed in the overarching research aim, this dissertation advances the understanding of how lean thinking can be applied to the execution of engineering design and its coordination with other ETO operations that differ from the more traditional operations reported in the extant BOK.

1.3. Research scope

The scope of this PhD research is the study of how ETO operations efficiently execute and coordinate engineering design. These project-based ETO operations make the PM theory a relevant theory to investigate (Cannas and Gosling, 2021). In this dissertation, PM is regarded as an extreme version of operations management, with defined timelines, high process variety, and low volumes. Focusing on ETO operations, the overall aim of this PhD research is to create and develop knowledge of how lean thinking can be adapted and applied to engineering design in ETO operations. As such, this PhD study does not discuss *whether* lean thinking can be applied to engineering design but *how* and *why*. Although important, a comprehensive discussion on the effects and the challenges of implementing lean thinking in all areas of the studied organizations is outside the scope of this research. Nonetheless, this PhD research acknowledges the lean methodology as an approach that affects virtually all aspects of an organization (cf. Liker, 2017).

This PhD research places itself within the realm of project-based environments as ETO companies offer customized products. ETO companies are highly important in Europe's economic structure, despite the significant challenges they face to remain competitive. It is essential to point out that most of the ETO companies involved in this study deliver products to the maritime industry, which imposes strict rules regarding the verification of design and production methods. This means that ETO companies should comply with all allowances set by governmental bodies and classification companies, as well as with the use of independent third-party verification companies. This industry practice may result in additional costs (as verification companies charge expensive fees) and delays. Moreover, all involved ETO companies can be classified as dealing with complex and basic ETO archetypes (as defined by Willner et al., 2016b and introduced more thoroughly in Section 2.1). This means that all case companies produce a low yearly volume of products that require a substantial amount of customer-specific engineering design.

1.4. How to read this dissertation

This dissertation is based on research that has been conducted and disseminated through the appended papers and serves the purpose of synthesizing and presenting these results. Although the dissertation is organized in two parts (the main report in Part 1 and the collection of papers in Part 2), it is intended to be read and understood without having to read the appended papers. However, when appropriate, a reference to the specific paper is provided to clarify details.

The remainder of Part 1 is organized as follows: Chapter 2, the theoretical foundation, provides an overview of the main BOKs related to this study, such as ETO operations, PM, and lean thinking. Chapter 3, the research design, describes the methodological assumptions of this dissertation, explaining in detail how the data were collected and analyzed. Chapter 4 presents the research results, and Chapter 5 discusses how these findings address the RQs and contribute to bridging identified research gaps. Finally, Chapter 6 concludes this dissertation and suggests contributions to theory and practice, as well as points at limitations and offers suggestions for future research. Figure 2 illustrates the outline of Part 1.

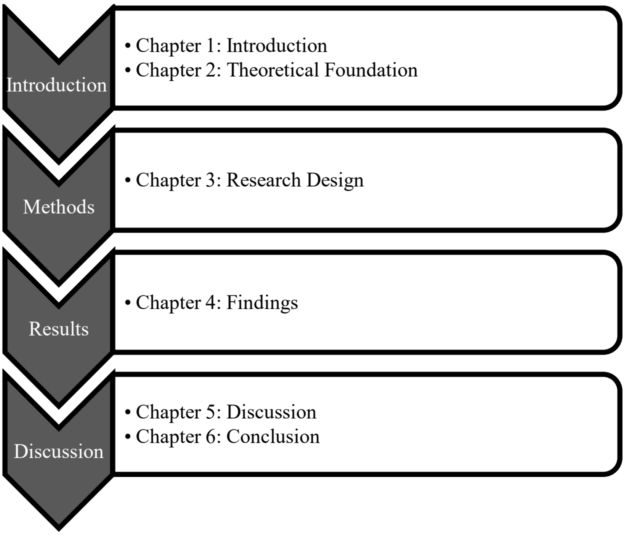


Figure 2. Dissertation’s outline

Part 2 includes the following four papers that disseminate the results of this PhD study:

Paper 1

Jünge, G. H., Kjersem, K., Shlopak, M., Alfnes, E., Halse, L. L. (2015). From first planner to last planner: Applying a capability model to measure the maturity of the planning process in ETO. *Advances in Production Management Systems: Management Towards Sustainable Growth,* 220–247. September 5–9, 2015, Tokyo, Japan.

Paper 2

Jünge, G. H., Alfnes, E., Kjersem, K, Andersen B. (2019). Lean project planning and control: Empirical investigation of ETO projects. *International Journal of Managing Projects in Business*, 12, 1120–1145.

Paper 3

Jünge, G. H., Alfnes, E., Emblemsvåg, J., Nujen, B. B., Kjersem, K. (2021). Understanding and eliminating waste in ETO projects: A multiple case study. *Production Planning & Control,* 1–17.

Paper 4

Jünge, G. H., Nujen, B. B., Alfnes, E. (under review). Lean practices assisting in overcoming unleveled workflow in engineering operations: A case study. *Engineering Management Journal.*

2. Theoretical Foundation

This chapter describes the theoretical foundation of this research, which deals with the challenges of executing and coordinating engineering design in ETO operations. These project-based ETO operations make the PM theory a relevant theory to investigate. With emphasis on the applicability of lean thinking, this chapter presents existing lean solutions and identifies the gaps that this dissertation aims to bridge. The chapter concludes with the research framework that guides this dissertation.

2.1. ETO operations

A number of authors have sought to define and categorize ETO operations, as well as offer insights into their complex nature (cf. Alfnes et al. (2021). Gosling and Naim (2009) define an ETO supply chain as process where production is customized for each order and where the customer participate in the design phase, often operating in project-based environments. Since ETO products either have to be fully developed or adapted to customer specifications (Amaro et al., 1999), engineering design tasks have to be conducted as early as tendering or order execution. This can lead to a range of coordination issues in terms of integrating engineering and production (Mello et al., 2015). Other researchers identify a number of ETO archetypes based on volume and the amount of order-specific engineering work to be performed. For example, Willner et al. (2016b) define engineering complexity as order-specific engineering hours divided by the average annual units sold and present four kinds of ETO archetypes (complex, basic, repeatable, and non-competitive). The ETO sector encompasses a broad range of industries, including mechanical engineering, construction, and shipbuilding (Cannas et al., 2019). Sanderson and Cox (2008) point out that the ETO environment (e.g., as found in shipbuilding and construction) also includes many different make-to-stock or fabricate-to-order components that do not need customized engineering design themselves but still require a unique or innovative configuration.

ETO customers often wish for short lead times (Schönsleben, 2012). Hence, ETO companies face the difficult prospect of undertaking order-driven engineering design activities while customers wait impatiently, often making last-minute requests for changes. This leads to unpredictable workflows, rush jobs, out-of-date information, and delayed delivery dates (Gosling et al., 2015). From an engineering design perspective, ETO might be considered the extent to which orders penetrate the scientific–technical flow of engineering design activities (Dixon, 1989). For this dissertation’s scope, the following four typical characteristics of ETO operations are important when studying engineering design.

First, ETO operations have a high level of uncertainty in product and process development during the early phases of engineering design. The product requirements are broadly defined in the beginning of the project and evolve iteratively as it proceeds (Hicks et al., 2001). These iterations, involving customers, suppliers, and authorities, create obstacles concerning quality, resource utilization, lead time, and customer satisfaction, among others (Adler, 1995, Braiden et al., 1993, Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002).

Second, ETO operations combine non-physical activities, such as engineering design and procurement (Amaro et al., 1999, Gosling and Naim, 2009, Wikner and Rudberg, 2005), with physical activities, such as component production, assembly, and installation (Bertrand and Munstlag, 1993). The non-physical activities are often geographically dispersed, separated from physical activities, and executed by individual entities. Consequently, the company that manages the overall project executes only a small part of the project that is performed by its own personnel and in its own production facilities. The greater part, often 75% or more, of the product’s value is built in global networks, with help from suppliers and subcontractors (Dubois and Gadde, 2000).

Third, to keep lead times short, engineering design, procurement, and production are often executed concurrently because not all design details and drawings are finalized when procurement of items with long lead times and production of components start (Birkie and Trucco, 2016, Gosling et al., 2015). Consequently, design changes affect component production at all supplier tiers, making it difficult to align and control production and engineering activities. Quality issues may arise, requiring rework (Bogus et al., 2005, Hicks et al., 2000, Maier et al., 2008, Mello and Strandhagen, 2011, Terwiesch et al., 2002).

Fourth, ETO operations are driven by tacit knowledge as they deliver unique and highly customized solutions based on expert competence and experience (Emblemsvåg, 2017). Consequently, individuals are at the center of defining the scope and the content of each activity needed to deliver the solutions (Hicks et al., 2000, Kjersem and Emblemsvåg, 2014, Mello, 2015).

The theory of OM can be used to distinguish between the traditional, repetitive production environment and the project-based environment, as found in ETO operations. OM is concerned with organizing work, which spans a spectrum, ranging from novel to repetitive or from variety to volume. Moreover, OM focuses on transformation processes, specifically the transformation of inputs into outputs. Inputs can be materials (e.g., in a manufacturing process), information (e.g., in an engineering design process), people (in a service), or organizations (e.g., in a change project) (Holweg et al., 2018). The output of transformation processes is described in a number of dimensions, including whether it is concerned with delivering a product, a service, or some combination of these, and its volume variety characteristics (Maylor et al., 2015).

The first dimension refers to the output of transformation processes and states that an output can be tangible, intangible, or a combination of both. Thus, processes can deliver products, that is, tangible outputs whose production precedes their consumption (e.g., the construction of a building). Processes can also deliver services, where the outcome is intangible and the service delivery is simultaneous with the process duration (e.g., a medical consultation). Finally, there can also be a combination of tangible and intangible outputs, meaning that a product-centric offering becomes a product and service offering through servitization (e.g., (Baines et al., 2009, Wikström et al., 2009).

The second dimension refers to the volume variety characteristics of transformation processes and distinguishes projects from other types of operations. This means that processes can be described according to the volume of throughput, where a high volume would be reflected in the use of a production line, for instance, or a service center (e.g., a call center). In such cases, the variety of processes used is deliberately kept very low to allow resources to be configured to meet the need of delivering the volume of throughput with the objective of maximum efficiency. Medium-volume processes with medium variety would be handled by jobbing systems, typically involving the use of more flexible technology, people, and processes in the transformation (Maylor et al., 2015). As such, projects are temporary, with a defined beginning and end, and with scope, time, and budget constraints.

2.2. Project management

The knowledge on how to manage projects is covered by the PM literature, where the practice of PM is acknowledged as different from those of other OM areas (Geraldi et al., 2011). The typical view of PM is that a *project* is temporary, while *operations* are more permanent or carry on business as usual. *Projects* have definite beginnings and endings, while *operations* are typically repeated over time. The traditional view of the budget in PM is that a *project* has to stick to a definite budget, while *operations* have to maintain a specific profit margin. Therefore, constraints from a defined project goal and budget, effective communication, commitment from senior management, as well as project planning and monitoring, have been recognized as contributing to project success during the execution phase (Pinto and Slevin, 1988).

The existing PM literature shows evidence that coordination of operations in project-based environments through planning and control is one of the main factors leading to either success or failure (Albert et al., 2017, Alderman et al., 2001, Andersen et al., 2007, Beauregard et al., 2011, Emblemsvåg, 2017, Emblemsvåg, 2020, Hoppmann et al., 2011, Hussein, 2013, León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011, Müller et al., 2012, Rolstadås et al., 2014). Coordination not only involves optimizing (or balancing) the available resources, the desired quality, or the available time by setting up the activities that need to be done, but it equally entails formulating a strategy of coordination for collecting and analyzing the information and data available to make the right decisions. As new knowledge becomes available or changes are requested, planned activities and available resources need to be reallocated. More project participants imply more information that leads to a higher probability of changes or adjustments, making the need for coordination even more evident. In his book, *Development Projects Observed*, Hirschman (1967) states that ETO operations can be defined as not mere tools but as forming an idiosyncratic network of experiences, human foibles, motivations, and creativity interacting with one another. Decisions and outcomes are based on participants' individual and collective judgments, experiments, and learning experiences (Ika and Söderlund, 2016).

2.3. Lean thinking

Lean thinking is an improvement philosophy, which focuses on the fulfillment of customer value and waste reduction. This philosophy was first introduced to the public as *the Toyota way of developing and manufacturing cars* in the book *The Machine that Changed the World* (Womack et al., 1990). The term *lean* was suggested by the Massachusetts Institute of Technology (MIT) graduate student, John Krafcik, who argued that lean would mean doing more with less. During a five-year study comparing Japanese, European, and American automobile industries, the MIT found that Japanese companies, especially Toyota, were doing more of everything they needed to do for the customer with less of almost everything (Womack et al., 1990). The American automobile industry, dominated by General Motors and Ford, experienced severe quality challenges at that time due to their existing management philosophy, including assembly lines, mass production, and work specialization. Both Americans and Europeans followed a conventional management philosophy, based on two 17th-century assumptions: (1) Order in any system must be created by a greater intelligence operating from outside the system. (2) Systems are predictable. In this case, the management's job is to tell people to follow the single best way (e.g., Taylorism). Modern science shows that order emerges from within certain kinds of systems and that most systems are unpredictable (e.g., systems theory). Therefore, lean management's job is to continuously help order emerge by learning and helping others to learn (Ward and Sobek II, 2007).

In their book, Womack et al. (1990) described lean thinking by five key principles (Table 1). The book quickly became the reference for any lean thinking initiative, whether in academia or industry (Rossi et al., 2017). Already then, this lean concept was applied to both routine work, such as shop-floor operations (expressed in the Toyota Production System [TPS]) and extremely non-routine work requiring special knowledge, such as design, engineering, and sales (expressed in the Toyota Product Development System [TPDS]) (Jones and Womack, 2016). Nonetheless, most of the interest and attention have focused on the TPS, with little curiosity about the TPDS. Although one system enhances the other's success, these two systems have evolved separately at Toyota, and it would be wrong to consider lean product development (LPD) as a consequence of lean production and a mere translation of lean manufacturing principles, theories, and tools into product development. It would also be incorrect to understand LPD as limited to describing the TPDS (Rossi et al. 2017). Before defining the LPD concept in more detail and showing how it has influenced other project-based environments, the term *value* should be introduced.

Table 1. Five lean principles, as defined by Womack and Jones (1996)

Number	**Principle**	**Definition**
1	Specify value	Define value precisely from the perspective of the end customer.
2	Identify value stream	Identify the entire value stream for each product or product family, and eliminate waste.
3	Make value flow	Make the remaining value-creating steps flow.
4	Let the customer pull value	Design and provide what the customer wants only when the customer wants it.
5	Pursue perfection	Strive for perfection by continually removing successive layers of waste as they are uncovered.

2.3.1. Value creation in ETO operations

A critical point in lean thinking is its focus on value. However, value creation is often perceived as equal to cost reduction. This represents a common yet critical shortcoming of the understanding of the lean methodology (Hines et al., 2004). According to Womack and Jones (1996), value is the first principle of lean thinking, making it explicit that value creation is more than mere waste and cost reduction (e.g., on the shop floor). Value needs to be linked to customer requirements; regardless of whether an activity appears wasteful (from the shop-floor perspective) or costly, the customer ultimately decides what constitutes and does not constitute waste.

In ETO operations, value assumes a specific meaning, and its creation starts with identifying what customers really want, followed by understanding and articulating customer-defined quality. Value is then actually created through an operational value stream of engineering design, procurement, and production, consisting of all the interconnected activities that contribute to value creation (Rossi et al., 2017), as illustrated in Figure 3.

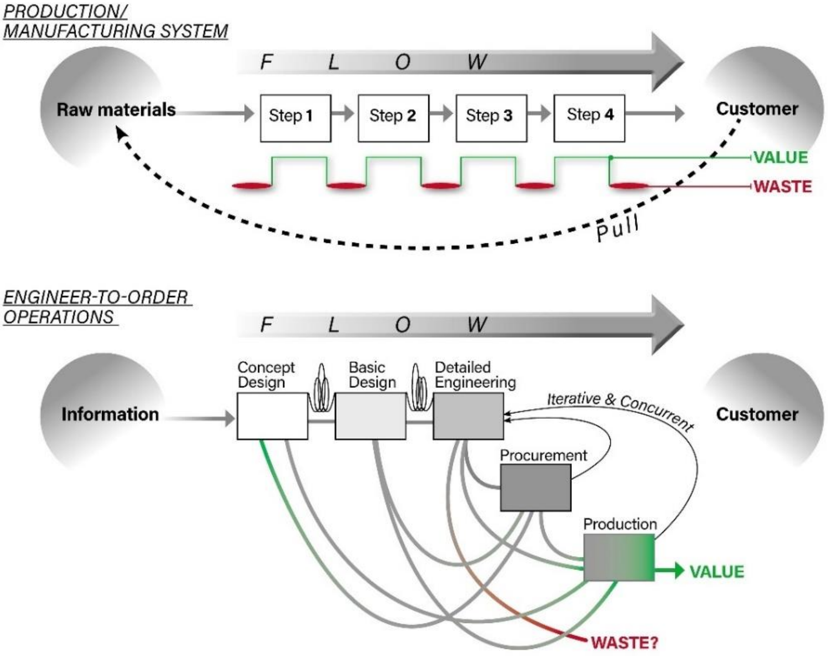


Figure 3. Value-creation model as applied to engineer-to-order operations (from Paper 3)

Against this backdrop, this dissertation follows the definition of Hines et al. (2004), who state that value is created if internal waste is reduced, as the wasteful activities and their associated costs are decreased, increasing the overall value proposition for the customer.

Contrary to value, the failure to generate customer-defined quality is waste (or *muda* in Japanese). Waste in engineering, as in any other process, is a symptom of not operating at high efficiency or effectiveness. However, waste in engineering is less visible and therefore more difficult to identify (Hicks, 2007). Many scholars have provided various definitions of waste because it disguises itself in different ways, according to the context in which it appears (Formoso et al., 1999, Koskela, 2004, Liker, 2017, Macomber and Howell, 2004, Mascitelli, 2007, Poppendieck, 2017, Womack and Jones, 2003). To understand waste, it is grouped into different categories; this article follows the classic categories of waste in manufacturing, as famously introduced by (Ohno, 1982). With some adjustments, these are applicable to engineering design (Rossi et al., 2017). Empirical studies have revealed that organizations spend over 50% of their time on pure non-value-adding activities (*muda*), and the rest is split between value-adding and non-value-adding-but-necessary activities (see, e.g., (Ballard, 2000a, Bonnier et al., 2015, Freire and Alarcon, 2000). The problem seems to be that engineers and designers are often not even willing to recognize that their jobs can produce waste (Browning, 2003, Rossi et al., 2017). Moreover, many organizations often limit their improvement efforts to *muda* reduction, which is insufficient to guarantee sustainable success (Morgan and Liker, 2006). Thus, it is vital to consider the causes of waste (referred to as *muri* and *mura* in Japanese) together with the waste itself. *Muri*, or overburden, means overloading resources. This results in long queues that increase engineering design lead time, or it introduces chaos to the engineering design process, which in turn causes mistakes. *Mura*, or unevenness, refers to an imbalanced work pace that forces people to hurry and then wait, among other problems (Rossi et al., 2017). *Muda, muri,* and *mura* are interrelated, and eliminating one of them will affect the other two. Therefore, several of the waste categories may form a natural part of the engineering design process, and it depends entirely on the situation if the activities should be defined as wasteful or not (Ballard, 2000c).

2.3.2. Leveled engineering design workflow

Another critical point in lean thinking is its focus on flow, defined as the third principle of lean thinking (Womack and Jones, 1996). Since the popularization of lean thinking and the TPS, manufacturing companies have strived to achieve a leveled and uninterrupted workflow (Liker, 2017) as it generates more reliable delivery and greater value to customers, teams, and stakeholders and has proven to be successfully implemented in production processes (Slomp et al., 2009). As previously stated, in addition to traditional production, ETO operations require substantial efforts in engineering design (Strandhagen et al., 2018) and lie at the heart of customized value creation.

However, engineering design has been proven to be packed with activities outside a leveled workflow, resulting in many stoppages. Its potential inefficiency might negatively affect the coordination of all other important and intertwined business operations, such as sales, procurement, and production (Braiden et al., 1993).

Over the last couple of decades, scholarly journals have published some articles that focus on lean practices to implement the lean philosophy, aiming to improve workflow, decrease lead time, and enhance overall performance (Deshmukh et al., 2010, Shah and Ward, 2003). For instance, Mirdad and Eseonu (2015) extracted 200 lean practices from 22 studies conducted between the 1990s and 2014. Shah and Ward (2003) identified 22 practices in the literature, which they combined in four bundles when addressing implementation aspects. Though important, these lists of practices refer mainly to production processes, with no specific focus on business processes, such as engineering design. In contrast, this dissertation is concerned with extracting lean practices that specifically focus on achieving a leveled engineering workflow.

Moreover, based on the empirical evidence provided by their important work, Willner et al. (2016b) argue that only a low level of engineering design standardization (and automation) is economically feasible for the complex ETO archetype and a medium level of standardization for the basic ETO archetype. Thus, this dissertation focuses on workflow leveling rather than on other known lean ideas, such as standardization.

2.3.3. Existing concepts that apply lean thinking to project-based environments

In recent years, research has shown that lean thinking can be applied to any level of an organization, for example, as a strategic management philosophy (Ballé et al., 2017), a planning system (Ballard, 2008), or an operations system that manages both physical operations, such as production (Found and Bicheno, 2016), and non-physical operations, such as development (Liker and Morgan, 2019). Moreover, lean thinking has been successfully adapted to project-based environments. Accordingly, valuable contributions of applying lean thinking as a means to respond to the shortcomings of traditional PM can be found in the BOKs of LPD (covering aerospace, automobile, or similar complex development projects), lean construction, lean shipbuilding, and lean (often called agile) software development. The following paragraphs briefly introduce each of them.

Ward and Sobek II (2007) and Morgan and Liker (2006) provide the two most influential contributions regarding the applicability of lean thinking to project-based environments by introducing lean product and process development (LPPD) and LPD, respectively. According to Ward and Sobek II (2007), LPPD should essentially create profitable value streams. Additionally, since LPPD is strongly based on learning and the creation and use of knowledge, the value of LPPD lies in the generation of (re)usable knowledge. Morgan and Liker (2006) view LPD as an interconnected structure consisting of a large number of resources, both human and technical, each involved in the complex and uncertain development process and contributing to value creation (Rossi et al., 2017). This view draws on the sociotechnical system theory, from which the authors derive the three main perspectives to be integrated into product development: people, process, and technology. LPD and LPPD differ from traditional product development by turning the sequence of designing–building–testing into testing–designing–building. This process is achieved by adhering to the following set of principles called set-based concurrent engineering (SBCE): (1) Explore and compare alternative options independently and in parallel. (2) Postpone design decisions as long as possible. (3) Generate reusable knowledge. (4) Engage different kinds of resources for problem-solving activities. (5) Strive for continuous improvements and (6) continuous learning (Liker, 2004, Rossi et al., 2017, Ward and Sobek II, 2007).

Other significant contributions should be cited. For example, Hoppmann et al. (2011) provide a new framework comprising 11 existing LPD components. Letens et al. (2011) present a detailed review of existing LPD literature, categorize their cited publications under nine knowledge domains, and provide extensive suggestions for future research. Liker and Morgan (2011) offer unique and valuable insights on how Ford created its own version of Toyota's

LPD. Haque and James-Moore (2004) apply LPD to the British aerospace industry, whereas Oppenheim (2004) reports his study on the US aerospace industry, suggesting a framework for LPD flow. Khan and Tzortzopoulos (2015) present their study on five engineering companies specializing in the aerospace, the automotive, or the home appliance industries. Nepal et al. (2011) report their study on LPD in a US company that manufactures moderately large and complex products used in office buildings. Further research worth mentioning includes Reinertsen's (1997) work on managing a design factory, which makes an important contribution to improving product development, although he never calls it lean (e.g., Smith and Reinertsen (1997)). Likewise, Mascitelli (2007) argues that the only way that a company can improve its product development is by changing how its employees work every day; accordingly, the author modifies the five principles of lean thinking.

Over many years, the construction industry has studied how lean principles can improve construction project performance, and many of the results are presented through the International Group of Lean Construction (IGLC). One of the main contributions of the IGLC regarding project planning is the Last Planner System® (LPS®) developed by Glenn Ballard (Ballard, 2000a). LPS® is a planning and control system that aims to combine the technical and the social aspects of the planning process in construction projects. The role of the LPS® is to increase planning reliability by decreasing workflow variability through recognizing and removing activity constraints, identifying root causes of non-completion of plans, and monitoring improvements by means of the Percent Plan Complete (PPC). The LPS® continuously seeks waste elimination or reduction, in this way deviating from the conventional PM approach. In essence, the planning and control system is designed to shift from the productivity focus to the physical and the non-physical flows that link the production units. The LPS® empowers control by forcing problems to be visible at the planning stage. The system is named after the people at the operational level, who commit to making reliable promises in the next period and are accountable for the fulfillment of such promises. These actors are true drivers of actual work rather than the further development of plans. The process executed by the LPS® ensures that activities *will* be done (based on the premise of the activities that *should* be done) by considering all type of constraints. The basis on which the LPS® is developed clearly distinguishes among *should, can*, and *will* to foster predictability.

To successfully achieve the *will* aspect of the LPS®, five ruling principles should be followed: (1) Plan in greater detail as the actors draw closer to doing the work. (2) Produce the plan collaboratively with those who will do the work. (3) Reveal and remove constraints to planned tasks as a team. (4) Make and fulfill reliable promises. (5) Learn from the mistakes made (Ballard and Koskela, 2009, Ballard and Tommelein, 2016).

The shipbuilding industry provides another important example of the application of lean thinking to project-based environments. Departing from the LPS®, Emblemsvåg (2014a) claims that this system is unable to handle advanced engineering design work. Instead, he advocates a better instrument that will be needed to measure the physical progress of such activities. In his attempt to deal with this challenge, Emblemsvåg (2014b) has developed and implemented a project planning approach that combines the LPS® and earned value management (EVM) features into a tool called Lean Project Planning (LPP). EVM is a technique that measures project performance and progress by comparing the project's baseline with the reported physical results, the resources consumed, and the remaining hours before completion per activity (Sumara and Goodpasture, 1997). Therefore, LPP is designed to address the specific characteristics and challenges of engineering management in the shipbuilding industry. LPP applies the Plan-Do-Check-Act (PDCA) cycle, which is one of the most fundamental concepts in the TPS and obviously in the planning process as well (Sobek and Smalley, 2008). PDCA consists of different steps. The first step (Plan) involves identifying, understanding, and analyzing the problem to understand its root cause and develop a possible solution and an implementation plan. The second step (Do) concerns putting the plan into action. During the third step (Check), the effects of the implementation are measured and compared with the target. In the fourth and final step (Act), two options are possible: either the success of the implementation is confirmed, or remedial action is needed if the solution fails to meet the requirements. Based on the scientific method of iteration, once a hypothesis is confirmed, repeating the cycle will further improve the knowledge and can bring the project team closer to the goal, usually toward more perfect operations and output. In the LPP context, PDCA involves making problems visible, finding proper solutions, checking the results, and acting on deviations (Emblemsvåg, 2014a).

The final example of applying lean thinking to a project-based environment can be found in lean software development. The Agile Manifesto, again a proactive response to the potential failures of the dominant traditional software development PM paradigms, borrows many principles from lean thinking (Beck et al., 2001). The values and the principles of Agile Project Management (APM) stand in contrast to those of the traditional PMBOK® (Poppendieck, 2017). Arguably, the most used version of APM, Scrum is characterized by its similarities to playing rugby. Scrum can be described as a way to restart the game after an interruption. Developed by Ken Schwaber and Jeff Sutherland, Scrum is a framework consisting of a set of principles that can be used in complex jobs where events cannot be predicted (Schwaber et al., 2013). Scrum builds on three pillars—transparency, inspection, and adaptation—allowing the team involved to have an accurate view of the facts throughout the project and if necessary, make the appropriate adjustments. Scrum has the following six characteristics: (1) flexible delivery, (2) flexible deadlines, (3) local teams, (4) frequent revisions, (5) collaboration, and (6) orientation of interfaces and behavior (Adrialdo et al., 2017). Table 2 summarizes the examples of lean concepts in project-based environments and their underlying ruling principles.

Table 2. Examples of lean thinking concepts in project-based environments and their underlying ruling principles (from Paper 2)

Lean concepts	**Project-based environment**	**Underlying ruling principles**
Toyota Product Development System (TPDS) / Set Based Concurrent Engineering (SBCE)	Aerospace and Automotive	Explore and compare alternative options independently and in parallel. Postpone design decisions as long as possible. Generate reusable knowledge. Engage different kinds of resources in problem-solving activities. Strive for continuous improvements and continuous learning.
Last Planner System (LPS)	Construction	Plan in greater detail as the actors draw closer to doing the work. Produce the plan collaboratively with those who will do the work. Reveal and remove constraints to planned tasks as a team. Make and fulfill reliable promises. Learn from the mistakes made.
Lean Project Planning (LPP)	Ship building	Apply cost performance indicators as part of EVM to measure project performance and progress by comparing the project's baseline with reported physical results. Ensure equal treatment of people. Impose discipline when holding meetings (e.g., attendance is required; people should come prepared).
Agile Project Management (APM) / Scrum	Software Development	Flexible delivery Flexible deadlines Local teams Frequent revisions Collaboration Orientation of interfaces and behavior

Before moving on to the research gaps that this dissertation aims to bridge, it is important to highlight some of the main challenges that organizations and managers may face when applying lean thinking to their operations. As stated, lean thinking has been developed through practice over decades, and its success is rooted in the fact that it infiltrates any aspect of an organization and encourages managers to organize operations differently from traditional ways. This includes not only how organizations develop and produce their products but also how they sell their products, source components, make forecasts, set up their accounting systems, train employees, divide responsibilities among departments, cooperate with suppliers, and so on. Some of the most dominant differences between lean thinking and the more traditional management approach, as observed in western organizations, are discussed in the following paragraphs.

In production, lean thinking challenges the assumptions that there is a tradeoff between quality and productivity and that larger batches result in lower costs. The interconnected set of practices, called the TPS, as described by Ohno (1982) and Shingo (1988) has proven small batches to be economically feasible. Lean thinking further challenges the idea of work specialization and supervision as it teaches frontline and support staff how to define and improve their own work, rather than relying solely on the expert engineers (see e.g., Dinero (2005) who documented the Training Within Industry system). Moreover, lean thinking engages the whole workforce in seeking improvements to their work and improves the performance of the system as a whole (Deming, 1986). Lean thinking also challenges traditional forecasting schemes as it encourages organizations to link activities and remove all kinds of buffers and delays, and with much shorter lead times, to use simpler planning systems driven by demand rather than by forecast. This focus on linking activities and removing buffers provides another example of how lean thinking differs from traditional management approaches. Lean thinking aims for flow optimization rather than resource optimization. This means organizing activities in an uninterrupted workflow rather than organizing activities to achieve a high level of resource utilization (Modig and Åhlstrøm, 2013). Finally, in PM and product development, lean thinking opposes the well-established waterfall principle and asks for collaborative planning of rapid releases.

2.4. Research gaps and research framework

2.4.1. Research gaps

The examples of approaches where existing lean concepts are applied to project-based environments, as presented in the previous section, provide valuable insights transferrable to engineering design, as found in ETO operations. However, the systems to which these approaches are applied have some differences. First, a typical ETO product is produced only once (or in very low numbers). As such, the engineering design process hardly involves finding the optimal production process (i.e., the engineering design effort cannot be capitalized through many sold items afterwards). Second, in cases where the ETO company owns the production facilities, the production supplier is given. Third, the project profitability needs to be evaluated upfront. Once the contract is signed, the project cannot be stopped. On the contrary, fines or penalties are imposed for incomplete or late fulfillment (Emblemsvåg, 2020). Fourth, although ETO operations follow a customization methodology, they have a higher potential for reusing manufacturing systems (e.g., maritime equipement compared with construction projects). Fifth, ETO operations normally deliver products to external customers who wait, while product development projects follow each company's internal schedule. This puts the entire project team under much pressure, and the need to plan and control the execution of engineering design and its coordination with other ETO operations, such as procurement and production, becomes paramount (Alderman et al., 2001). Additionally, customers typically impose strict reporting and control regimes in an effort to manage their risks (Emblemsvåg, 2017).

The current literature on lean thinking advocates lean thinking principles as just as applicable to and effective in non-physical and non-repetitive operations as in more traditional production (Beauregard et al., 2011, Hoppmann et al., 2011, León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011, Nepal et al., 2011). However, Gosling et al. (2015) heighten the danger of using one solution from one scenario to another to create the so-called "candidate solution." In other words, there is a need for more research that aims to respond to this concern by incorporating reality with theory using in-depth case studies (León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011). This leads to the first research gap that targets the need for adapting lean thinking to new contexts (i.e., the importance of context translation), in addition to covering the need for more in-depth case studies, which are scarce in the extant BOK (León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011).

Customization and ultimately, value generation in ETO operations are achieved through an iterative process between engineering design and other involved ETO operations. Although inevitable, this iterative approach allows much leeway for waste generation, expressed in higher costs, quality defects, and longer lead times (Ballard, 2000c, Bonnier et al., 2015, Freire and Alarcon, 2000, Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002). Accordingly, the second research gap calls for more research to investigate engineering design in current practice, which will allow a discussion on how its inefficient execution and coordination create waste (Ballard, 2000c). Additionally, waste management is identified as a crucial approach to performance improvements, although few empirical examples can be found outside the automobile industry (Liker, 2017). Waste in engineering design is also less visible and therefore more difficult to identify, requiring more research on how to define and eliminate waste in engineering design (Hicks, 2007).

Finally, while lean thinking has a promising potential to improve ETO operations (Buer, 2020), the prevailing literature on lean thinking in ETO operations has mostly been applied to business areas, such as production (cf. the opposite of engineering design), where it has proven its feasibility regarding continued improvements, waste reduction, and shortened lead times (Netland and Powell, 2017, Powell and Van der Stoel, 2017, Strandhagen et al., 2018). This leads to the third research gap that points at the need for more research to increase the understanding about the applicability of lean thinking to engineering design (Birkie and Trucco, 2016, Black, 2007, Hoss and Schwengber ten Caten, 2013, Jasti and Kodali, 2015, Johansson and Osterman, 2017, Towill, 2007, Viana et al., 2014, Yadav et al., 2019). Table 3 summarizes the literature gaps that this dissertation aims to bridge.

Table 3. Identified literature gaps that this dissertation aims to bridge

Identified gap in literature	**References**	**RQ(s) addressing the gap**
More research is needed to investigate how lean thinking needs to be adapted to new contexts in addition to covering the need of more in-depth case studies.	Beauregard et al., 2011, Gosling et al., 2015, Hoppmann et al., 2011, León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011, Nepal et al., 2011	1–2
More research is needed to investigate engineering design in practice, which will allow a discussion on how its inefficient execution and coordination create waste.	Ballard, 2000c, Bonnier et al., 2015, Freire and Alarcon, 2000, Hicks, 2007, Liker, 2017, Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002	1–2
More research is needed to increase the understanding about the applicability of lean thinking to engineering design in ETO operations.	Alderman et al., 2001, Birkie and Trucco, 2016, Black, 2007, Emblemsvåg, 2017, 2020, Hoss and Schwengber ten Caten, 2013, Jasti and Kodali, 2015, Johansson and Osterman, 2017, Towill, 2007, Viana et al., 2014, Yadav et al., 2019	3

2.4.2. Research framework

To examine the relevant theory and to address the identified research gaps through the fundamentals of lean thinking, a conceptual framework was constructed. A conceptual framework is used to outline the researcher's approach to an idea or a proposition. It is the lens through which the problem is viewed. In other words, this research tool is intended to assist the researcher in developing an awareness and an understanding of the situation under scrutiny (Miles et al., 1994). As visualized in Figure 4, this PhD study places engineering design at the center of its investigation, specifically the operations of executing engineering design and its coordination with other ETO operations. Being applied to a project-based environment, the PM theory is vital to study. Moreover, as the research aim is to investigate how lean thinking can be adapted and applied to engineering design in ETO operations, it is crucial to thoroughly explore lean thinking.

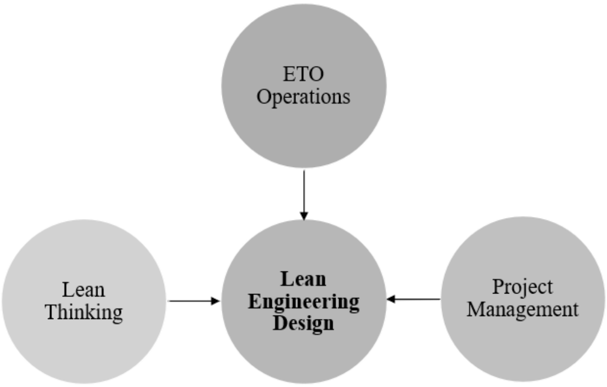


Figure 4. Research framework for studying how to adapt and apply lean thinking to the execution of engineering design and its coordination with engineer-to-order (ETO) operations

3. Research Design

This chapter gives an overview of the research design and describes the research methods, data collection and analysis procedures applied to answer the proposed RQs. It presents the six phases of design science that were followed: problem identification and motivation, objectives of solution, design and development, demonstration, evaluation, and knowledge dissemination. The chapter concludes by describing how the quality of research has been assessed.

Research can be described as a voyage of discovery, where knowledge is searched for through objective and systematic methods for finding solutions to a problem. Research design is the logical sequence that connects the empirical data to the study's initial research questions and its conclusion (Yin, 2014). It is a systematic process of solving research problems and includes mapping of which procedures and techniques that are suitable for researching the particular phenomena (Rajasekar et al., 2006). The design guides the process of collecting, analyzing, and interpreting data. Not all research questions can be answered by all research methods, and the design of the research method should therefore ensure a god fit between the research question asked, the method applied and the intended contributions of the study (Karlsson, 2009). However, the sequence of a research process does not follow a neat pattern but rather a messy interaction between the conceptual and the empirical world, deduction and induction occurring at the same time (Gill and Johnson, 2010). Good research ideas are rarely derived directly from literature and usually numerous contextual factors shape the, *what, why* and *how* of research such as the researcher's background and experience, academic and corporate stakeholders, trends in the field of the study, etc. Often the literature-based justification and anchoring only takes place post hoc (Easterby-Smith et al., 2002). This PhD research has been no exception. For others to evaluate the research conducted during this PhD study, this chapter describes the choices that have been made regarding research methodology, including research phases, research methods, data collection and analysis procedures. Each individual article, as presented in Part 2 of this dissertation, contains methodological description that supplements those given in this chapter.

3.1. Research tradition and influence of the researcher's background

There are clear differences between operations management (OM) research traditions in Europe and the US (Drejer et al., 2000). American research has often been based on larger surveys of phenomena in industry with an effort to reach statistical significance and reliability. There are often narrow research questions that are studied in detail. Methods are often quantitative with large databases. In contrast, European research has often been based on the researcher working in or close to industry. Issues are often cross-disciplinary with a focus on the whole plant or worksite. The studies are often based on a small sample, are usually wide in scope and may be longitudinal. A subset of the European tradition is the Scandinavian approach (Drejer et al., 2000). Typically conducted in small countries with small populations but with researchers even more integrated in organizations than elsewhere in European research. In line with the Scandinavian approach to research in OM, this PhD research combines insights from literature and data from empirical studies to identify relevant topics which can attract the attention of both academics and practitioners. Data were collected and analyzed in close cooperation with ten companies.

Moreover, the research aim and objectives have been influenced by the researcher's background in project management, her working engagement as head of the logistics group at Møreforsking AS (a research institute) during the PhD period, and her positioning within the research group at the Department of Mechanical and Industrial Engineering at NTNU. The department has an extensive publication record on lean thinking as well as a heavy focus on research with industrial relevance and applicability. The combination of conducting this PhD study and simultaneously managing a portfolio of approximately 20 different research projects provided an excellent arena for the researcher to combine the acquisition of theoretical knowledge in relevant fields with practical application in real-world contexts.

3.2. Research in operations management (OM)

As research in OM addresses issues relevant for both the academics and the practitioners, OM research can contribute to the knowledge of academics and development of the field, as well as to the knowledge of practitioners and development of skills in managing operations (Karlsson, 2009). The aims of research in OM are often related to good practice. Relevance is also crucial as it is closely linked to practice. This PhD research is therefore placed in the core aim of OM, as it aims to understand current needs for practical relevance as well as developing theory to contribute to academic needs. In this study, operations are referred to as the way in which products, that is, goods and services, are produced. Operations include transformation activities: transforming resources, thus, converting inputs into outputs. Within this general definition by (Karlsson, 2009), we all perform operations and operations go on all around us.

There are some characteristics of the OM research field that influence how we deal with it. It is an applied field with a managerial character. It deals with issues and problems encountered in the so-called real world. It is cross-disciplinary drawing on disciplines such as economics, finance, accounting, organizational behavior, marketing, mathematics and more. Different schools of thought within OM have developed in different academic organizations. The European universities of technology (such as NTNU and this PhD study) have focused often on the needs of engineers in future managerial positions, including production system design, layouts, production technology, the control of material flows, statistical quality control, allocation and utilization of plants and equipment, planning techniques, managing the production function, organization of line and staff in production, wage systems, productivity measures, product cost calculations, work organization and worker safety. Business schools within Europe have, on the other hand, focused on the needs of the general manager, studying investment calculations, product cost calculations, and allocation and utilization of plant and equipment.

3.3. Industrial need for research

This PhD study was part of LIFT (Effective global value chains for the production of maritime cranes and handling systems) research project. LIFT was a three-year research project funded by the Norwegian Research Council's program MAROFF (maritime activities and offshore operations) and its consortium consisted of academics and industrial partners from the Norwegian maritime cluster, with the research institute Møreforsking Molde as the overall project coordinator.

The case companies represented ETO companies in the maritime industry in Norway, delivering highly complex and customized equipment for the offshore industry. Lead times could vary from 9 to 12 months. Each solution was highly customized and designed to meet individual customer requirements. The main business activities of the case companies were engineering design, PM, production, assembly, installation and maintenance.

Thus, ETO products within the oil and gas industry were notoriously known for many changes and heavy customer involvement. Accordingly, LIFT emerged as a response to the increased global competition and cost pressure and fierce drop in demand due to low oil prices experienced by many of the case companies that suddenly found themselves in a battle for survival. High productivity seemed to be more important than ever.

3.4. Design science research (DSR)

This PhD study aims to contribute both to knowledge creation and to solving a relevant and interesting industry problem. Given this purpose, the study is designed and conducted under the design science paradigm. Design science "has its roots in engineering and the sciences of the artificial" (Hevner, 2007). The well-known *The Sciences of the Artificial* by Simon (1996) lays the foundations of design science.

This paradigm has been found effective in developing both relevant and valid knowledge to solve practical problems identified in industry (Hevner, 2007). Design science research (DSR) is conducted under many different rubrics: action science, action research, action innovation research, participatory action research, participatory case study, academe-industry partnership, and the like (Holström et al., 2009). Whatever the name, the common goal is the same: the researcher is interested in developing ‘a means to an end’, an artefact to solve a problem. Either the means or the end, or both, must be novel. In other words, DSR studies are driven by real-world problems and aim to develop general and prescriptive knowledge to support the design of solutions to practical industrial problems such as the ones described in chapter four, section 4.1.1. (Van Aken and Romme, 2009). Combined with the evaluation of the results, the artefacts represent the outcomes of the DSR process (Peffers et al., 2007).

Accordingly, using DSR, this PhD study argues that its proposed *lean engineering design* concept can serve as an artefact to guide practitioners working in ETO operations during the transition to a leaner approach. Different models of DSR processes exist (Eekels and Roozenburg, 1991, Hevner, 2007, Nunamaker Jr et al., 1990, Peffers et al., 2007). Peffers et al.’s (2006) was chosen for its comprehensiveness and clarity which consist of six steps, and these are presented in the following section.

3.4.1. Problem identification and motivation

During the first step the specific research problem is defined, and the value of a solution is justified. Since the problem definition will be used to develop an effective artefactual solution, it may be useful to atomize the problem conceptually so that the solution can capture the problem’s complexity. Justifying the value of a solution accomplishes two things: it motivates the researcher and the audience of the research to pursue the solution and to accept the results and it helps to understand the reasoning associated with the researcher’s understanding of the problem. Resources required for this activity include knowledge of the state of the problem and the importance of its solution (Peffers et al., 2007). Therefore, during the first phase the problem was framed by defining the characteristics of ETO operations (section 1), investigating the challenges related to unleveled workflow often leading to poor execution of engineering design (section 4.1.1.) Moreover, it was found that the iterative interaction of engineering design with other ETO operations challenged coordination which resulted in many forms of waste (section 4.2.1).

3.4.2. Objectives of solution

During the second step, the objectives of the solution are defined with the help of the problem definition. The objectives can be quantitative, e.g., terms in which a desirable solution would be better than current ones, or qualitative, e.g., where a new artefact is expected to support solutions to problems not previously addressed. Resources required for this include knowledge of the state of problems and current solutions and their efficacy, if any (Peffers et al., 2007). Accordingly, during the second phase, the current practice of executing engineering design and its coordination was thoroughly studied through an extensive multiple case study to get a deeper understanding of used solutions within industry.

3.4.3. Design and development

During the third step, the artefactual solution is created. Such artefacts are potentially, with each defined broadly, constructs, models, methods, or instantiations (Hevner, 2007). This activity includes determining the artefact's desired functionality and its architecture and then creating the actual artefact. Resources required moving from objectives to design and development include knowledge of theory that can be brought to bear as a solution (Peffers et al., 2007). Correspondingly, two artefactual solutions were designed and developed in close cooperation with ETO companies. First, following a literature study, a list of 20 lean practices (section 4.1.2) targeting the improvement of poor execution of engineering design, and second, following a maturity model methodology, a set of nine lean enablers (section 4.2.1) targeting the improvement of poor coordination of engineering design with other ETO operations, were designed and developed.

3.4.4. Demonstration

During the fourth step, the efficacy of the artefact to solve the problem is demonstrated. This could involve its use in experimentation, simulation, a case study, proof, or other appropriate activity. Resources required for the demonstration include effective knowledge of how to use the artefact to solve the problem (Peffers et al., 2007). Accordingly, during the fourth phase, the usefulness of the proposed artefactual solutions were demonstrated by holding company workshops and attending relevant conferences.

3.4.5. Evaluation

During the fifth step, the research observes and measures how well the artefact supports a solution to the problem. This activity involves comparing the objectives of a solution to actual observed results from use of the artefact in the demonstration. It requires knowledge of relevant metrics and analysis techniques. Depending on the nature of the problem venue and the artefact, evaluation could include such items as a comparison of the artefact's functionality with the solution objectives from phase 2 above, objective quantitative performance measures, such as budgets or items produced, satisfaction surveys, client feedback or simulations. At the end of this activity the researchers can decide whether to iterate back to phase 3, to try to improve the effectiveness of the artefact, or to continue communicating and to leave further improvement to subsequent projects (Peffers et al., 2007). Therefore, during this phase, the proposed artefactual solutions were evaluated regarding relevant metrics by asking how lean thinking can be applied to improve ETO operations (4.3). More specifically, the following metrics were evaluated: (1) To what extend do the proposed lean practices improve the execution (as expressed in workflow) of engineering design (section 4.3.1)? (2) How well do the proposed lean enablers minimize the key wastes (section 4.3.2)? and (3) How easy can lean enablers be implemented (section 4.3.2)?

3.4.6. Knowledge dissemination

Finally, during the sixth step the problem and its importance, the artefact, its utility and novelty, the rigor of its design, and its effectiveness to researchers and other relevant audiences, such as practicing professionals, when appropriate, is communicated. In scholarly research publications researchers might use the structure of this process to structure the paper, just as the nominal structure of an empirical research process. Knowledge dissemination requires knowledge of the disciplinary culture (Peffers et al., 2007). Consequently, although represented as the final phase, research problems, relevance, novelty, and results were disseminated consecutively through presentations, industry workshops, lectures, conferences, journal articles, and finally this PhD dissertation.

3.5. Research methods

During the six phases of DSR, several research methods have been used. First, several literature reviews were conducted to map the current knowledge and research gaps regarding the applicability of lean thinking to engineering design in ETO operations. Second, a single in-depth case study provided knowledge on the applicability of lean practices to overcome unleveled workflow in engineering design. Third, to identify lean enablers as well as to map current practice, a maturity model design method was followed. Fourth, an extensive multiple case study of 10 ETO companies provided insights on the key wastes found in engineering design and increased our understanding about the potential impacts of lean enablers on wastes. Table 4 provides an overview of the research processes by showing the relationship between research phases, research questions, research methods, main outcomes, and papers.

Table 4. The research process showing the relationships between design science research (DSR) phases, research questions, research methods, main outcomes, and papers published

DSR Phase	***Research Question***	***Method***	***Main Outcome***
1-6	*RQ1 How can lean thinking be adapted to the execution of engineering design?*	Literature review Single case study (case B)	New knowledge regarding the main challenges that hinder a leveled workflow of engineering design. (Section 4.1.1.) Presentation of lean practices (as part of the design science artifact) that can improve unleveled engineering design workflow. (Section 4.1.2.) Presentation of empirical evidence that describes the potential linkage between lean practice and challenges found in ETO operations. (Section 4.3.1.) **[Paper 4]**
1-6	*RQ2 How can lean thinking be adapted to the coordination of ETO operations?*	Literature review Multiple case study (cases A-J) Maturity model design	Presentation of existing solutions as found in lean thinking and evaluation of how these can be adapted to coordinating engineering design in ETO operations. (Section 2.3.2.) New knowledge on current practice of coordinating engineering design with other ETO operations, including a list of most common wastes. (Section 4.2.1.)

			New knowledge that increases the understanding how elements of lean thinking can be adapted to improve the coordination of ETO operations. Presentation of lean enablers (as part of the design science artefact) that enhances the coordination of ETO operations through elements of lean thinking. (Section 4.2.2) **[Paper 1 and Paper 2]**
4, 5 & 6	*RQ3 How applicable is lean thinking to engineering design?*	Multiple case study (cases A-J)	New knowledge regarding the characteristics of ETO operations and how these impact engineering design. (Section 1.) Presentation of empirical evidence that describes how lean practices can be applied to improve the execution of engineering design by leveling workflow. (Section 4.3.1.) Presentation of empirical evidence that describes how lean enablers can be applied to improve the coordination of engineering design with other ETO operation by reducing wastes. (Section 4.3.2.) **[Paper 3 and Paper 4]**

While used research methods are thoroughly described in appended research papers, the following section gives a short summary.

3.5.1. Literature review

A fundamental and natural starting point for any research process is to review the existing literature in the field of interest. It helps to gain an in-depth understanding of existing challenges and solutions, guides the development of research questions and research scope. Moreover, it gives justification for the choice of research methodology, and the review process itself contributes to developing the researcher's research skills (Åhlström, 2016).

Based on the importance of literature reviews, several reviews of relevant literature were undertaken during the first two phases of the research process. During the first phase, a literature review on the characteristics of ETO operations broaden our understanding of how these characteristics create challenges for engineering design. The main databases used for investigating these characteristics were Google Scholar, Science Direct, Emerald, and NTNU BIBSYS / Oria. No specific preferences were given regarding choice of literature, however, the researchers decided to only investigate journals of a certain quality in terms of their acknowledgement in academia. The most relevant papers were grouped thematically, then closer analyzed. The number of papers were expanded with the help of the initial ones, also referred to as the snowballing technique (Ang, 2014). During the second phase, objectives of the potential solution needed to be formulated, hence a literature review of existing lean solutions for similar project-based environments regarding the coordination of multiple operations was conducted as well as a literature review of existing lean practices that improve the execution of engineering design, helped to formulate the objectives of an improved solution. Regarding existing lean solutions for coordination, the literature review was based on the following search terms: Plan-Do-Check-Act (PDCA), Last Planner System (LPS®), Lean Project Planning (LPP), Lean Product Development, and Scrum (Agile Software Development). In order to gain an understanding of the different lean practices that can improve the execution of engineering design, suggested by leading researchers in the field, the literature review relied on: 1) the components of lean as defined by (Morgan and Liker, 2006, Ward and Sobek II, 2007); 2) the characteristics of current best practice and future suggestions found in the studies of the EMJ 2011 special issue on lean product development (Beauregard, Bhuiyan, & Thomson, 2011; Hoppmann, Rebentisch, Dombrowski, & Zahn, 2011; León & Farris, 2011; Letens, Farris, & Van Aken, 2011; Liker & Morgan, 2011; Nepal, Yadav, & Solanki, 2011), and 3) work of the following researchers (Ballard et al., 2002, Cusumano et al., 1998, Duggan and Healey, 2016, Haque and James-Moore, 2004, Liker, 2017, Mascitelli, 2007, Nonaka and Takeuchi, 1995, Oppenheim, 2011, Reinertsen, 1997, Tommelein et al., 1999).

Once a list of articles was identified, all involved researches used record sheets (Hart, 2018) to record relevant aspects (e.g., definition of lean practice, underlying lean thinking, area applied to, author, year). An initial list of 21 practices was identified and later combined into ten common themes (e.g., takt, pull, capacity utilization, learning).

3.5.2. Maturity model development

Maturity models (MM) have been available for decades and are used by scholars and practitioners, with the scope of identifying the current state of the focus process and comparing it with the desired state. A MM's strength lies in offering researchers and practitioners a simple and effective tool for analyzing and measuring business performance. The approach was first introduced in two articles by Crosby (1979) and Nolan (1979). Since then, MMs have become widely used, and several authors have demonstrated a positive relationship between maturity of performance (Evans, 2004) and managerial practice with better performance (Bititci et al., 2011, De Leeuw and Van Den Berg, 2011), which is the fundamental assumption of MMs. Furthermore, MMs with certain characteristics promote organizational learning and enable an efficient and effective assessment of the organization's performance management practice, leading to stronger managerial capabilities (Bititci et al., 2014). Bititci et al. (2014) refer to, among other things, the actual design of the MMs, where the users should be actively involved in defining the content and the assessment modes to gain their commitment and ownership of MM.

A typical MM comprises a set of sequences of levels for a class of objects, where each level represents an anticipated, desired, or typical evolutionary path of these objects, formed as discrete stages (Becker et al., 2009). This definition was used as a starting point for the conceptual design of the MM, as it follows a DSR development process according to Hevner's guidelines (Peffers et al., 2007). Becker et al. (2009) proposed a seven-step development process, but the maturity model developed as part of this dissertation used only four. This choice of approach is similar to those of earlier studies (e.g., (Neff et al., 2014, Nesensohn et al., 2014, Willner et al., 2016a). The four steps are: (1) problem definition, (2) comparison of existing MMs, (3) iterative development and (4) validation.

Since a MM should be developed iteratively (Wendler, 2012), the proposed MM had three rounds of iterations. The first round resulted in an early version of this study's conceptual MM based on the requirements for good planning and control found in the literature and the data from the preliminary interviews. During the second round, the research team refined the framework by presenting and discussing the results with the representatives from all case companies (Yin, 2014). In the third round, the researchers defined the maturity levels of three case companies by applying the model, and they presented the results at the annual Advances in Production Management System (APMS) conference in 2015 (Paper 1). To define the maturity of the planning and control process, representatives from engineering, procurement, project management, and production departments were involved. The MM concept was introduced to the group, followed by individual interviews. A minimum of two researchers conducted the interviews, with one as the main interviewer and the other as the note taker (Voss, 2008). A more detailed description of MM development method can be found in Paper 2.

3.5.3. Case study research

Case study research has consistently been one of the most powerful research methods in OM, particularly in the development of new theory. This research applies a case study approach as it provides explanation for contemporary social phenomena in their natural settings and cultural contexts, and are especially suitable for investigating phenomena in highly complex contexts, such as ETO operations (Stuart et al., 2002, Yin, 2014). The case study approach generates new insights, which are difficult to gain through purely analytical or statistical analysis (Meredith, 1999, Yin, 2014).

More specifically, as pointed out, this dissertation applies a Scandinavian case study research approach, allowing the researchers to engage in deep collaboration with a few selected case-companies. According to Karlsson (2009), this approach is suitable when aiming to develop academic and company-level knowledge simultaneously. However, there are several challenges in conducting case study research: it is time consuming, it needs skilled interviewers, and care is needed in drawing generalizable conclusions from a limited set of cases and in ensuring rigorous research. Despite this, the results of case research can have very high impact (Voss, 2008).

Moreover, when conducting case studies, the selection criteria are of crucial importance, because the knowledge derived from the selected cases should provide valid information to support the explanations when aiming to build or further develop theory (Eisenhardt, 1989). Ten case companies were selected that deliver ETO products mainly within the maritime industry, such as offshore-specialized vessels, cranes, technologically advanced pressurized vessels, propellers, thrusters, and casting equipment. The following inclusion criteria were included, thus, the companies should, 1) deliver mainly ETO products, 2) have ongoing initiatives that implement lean thinking concepts and 3) be willing to provide the involved researchers with relevant access to data and procedures to ease the mapping of targeted engineering design processes. Table 5 gives an overview of the companies that have participated in this research and the number of hours spent at each company for data collection and validation, also showing the number of customer specific engineering hours and units sold per year. Referring to the four ETO archetypes as defined by Willner et al. (2016b), these ten companies were considered to be representative for companies dealing with complex and basic ETO operations.

Table 5. Case companies' characteristics and data collection

Case	Market Segment	No. of Employees	T/O MNOK (2016)	No. of units sold)	Engineering (hours/ unit)	No. of h with data collection	Participated in design science research phases
A	Advanced equipment to maritime industry	>40	>180	<50	500-1.000	>50	1-5
B	Advanced equipment to casting industry	>50	>300	<50	10.000-15.000	>50	1-5
C	Advanced equipment to maritime industry	>30	>80	<20	25.000-30.000	>50	1-5
D	Advanced equipment to maritime industry	<10	>15	<50	5.000-10.000	>50	1-5
E	Advanced vessels to maritime industry	>500	>4800	<20	>50.000	>20	1-5
F	Advanced vessels to maritime industry	>300	>3700	<20	>50.000	>10	1-2
G	Advanced equipment to maritime industry	n/a	n/a	<100	500-1.000	>10	1-2
H	Advanced equipment to maritime industry	>1900	>400	<100	5.000-10.000	>50	1-5
I	Advanced equipment to maritime industry	>600	>200	<150	100-1.000	>200	1-2
J	Advanced vessels to maritime industry	>650	>250	<20	>50.000	>20	1-2

In case study research there is often the temptation to do "just one more case" or "just one more interview" to test some to the emerging theory or to get greater insight into the research questions. Knowing when to stop is an important skill of a case researcher. Over the past five years, we have visited over ten companies with the expressed purpose of exploring what works and what does not work in executing engineering design and in coordinating engineering design with other ETO operations. Using explorative case study techniques, we asked practitioners to relate stories about current practices and challenges encountered. From this rich set of stories, we uncovered patterns of wasteful activities which ultimately led us to introduce elements of lean thinking that potentially could be implemented or considered implemented in engineering design. Throughout the research process, our understanding of current practice, challenges and our definitions of the applicability of lean thinking evolved with each new or return company visit, serving to reinforce or reshape our emerging concept of *lean engineering design.* Our approach was consistent with the prescriptions for case study research of Eisenhardt (1989) in that we intentionally selected theoretically useful cases, used multiple (two-three) investigators, considered qualitative and quantitative data and allowed the study to change course as themes emerged.

3.6. Research quality

The quality of OM research, can be judged according to four particular requirements: construct validity, internal validity, external validity and reliability (Karlsson, 2009). The following subsections present examples of strategies that have been applied during the research process to account for the four facets of research quality.

3.6.1. Construct validity

Construct validity is the extent to which we establish correct operational measures for the concepts being studied (Voss, 2008). To adequately account for construct validity, Yin (2014) proposed two critical aspects; (1) provide clear definitions of what is to be investigated, and (2) show that the operational measures do indeed reflect what is intended to be measured. In this study, definitions are provided in the appended papers where some ambiguity might exist regarding the concepts being studied. The clear and thorough discussion of the development of the construct used in the research is based on a critical analysis of the literature and iterative empirical data analysis. For example, the development of the concept of lean engineering design was iteratively following the steps of maturity model development as suggested by (Becker et al., 2009). Three rounds of iterations contributed to construct validity. The first round resulted in an early version of this study's conceptual maturity model based on the requirements for good planning and control found in the literature and the data from the preliminary interviews. During the second round, the research team refined the concept by presenting and discussing the results with the representatives from all case companies. In the third round, the researchers defined the maturity levels of three case companies by applying the model; The results were presented at the annual conference of Advances in Production Management System (APMS) in 2015 (Paper 1).

Moreover, to minimize concerns for the construct of validity, multiple methods for data collection (e.g., targeted interviews, observations, meeting minutes from planning meetings, company documents and the information obtained through the research team's participation in companies' workshops) and data analysis (e.g., checklist matrix based on Miles et al. (1994), see Appendix C) were applied.

3.6.2. Internal validity

Internal validity refers to establishing the correct causal relationship, not overlooking other factors that could explain these relationships (Karlsson, 2009). In other words, if it is concluded that Y has taken place because of X but overlooked that Y really happened because of Z there is low internal validity. To ensure internal validity, several strategies were followed throughout the research process. For instance, as emphasized by scholarly literature, a multiple case study design was chosen, considering the benefits of enhanced validity (Eisenhardt, 1989).

Another example is that data were collected and analyzed by a research team, rather than a single researcher, improving its creative potential, which allowed for the convergence of observations to strengthen confidence in the findings (Voss, 2008). Interview data, notes and documentation of the research process have been managed carefully and in a retrievable form. The collected material in this dissertation can therefore be made available to other researchers for auditing, thus enhancing the validity of conclusions (Lincoln and Guba, 1990). Internal validity was also improved by what Lincoln and Guba (1990) refer to as peer briefing, which is the important exercise of exposing one’s work to other researchers or practitioners that are qualified to evaluate and comment on the work. As noted, a working engagement at Møreforsking Molde allowed the presentation and discussion of preliminary findings at workshops and seminars, organized by other ongoing research projects, throughout the research process.

Moreover, preliminary concepts and findings were presented at international conferences (e.g., EurOMA 2016 , APMS 2015 and PMA 2016). The peer briefing criteria has therefore been ensured not only by the involved parties (both practitioners and researchers) in the LIFT and similar research projects, but also by academics in OM and project management field, which can contribute to a further dimension of interpretation that goes beyond the subjective interpretation made by the researcher(s) (Creswell et al., 2007).

Finally, a useful strategy for obtaining internal validity is to discuss the findings with participants to see if they agree. For example, the findings related to RQ2 showed a low level of maturity of lean planning and control (as part of coordination), supporting both previous research (see e.g., (Adrodegari et al., 2015, Emblemsvåg, 2017, Koskela and Howell, 2002, Little et al., 2000) and the empirical evidence that laid the foundation for the research. All case study participants agreed that the nine enablers of *lean engineering design* were important for the successful coordination of ETO operations. They also acknowledged that different maturity levels were achievable and that the measurements were realistic (see paper 2). Another example relates to the investigation of the 'fitness' of the identified lean practices (related to RQ1). Although validating the suitability and usability (cf. fitness) of the proposed lean practices is a difficult task (León and Farris, 2011), its validity has been assured through ongoing improvement iterations with the practitioners. Over a six months period, two to three lean practices, were thoroughly introduced to the case organization at a time (comprising representatives from sales, project management, engineering design, production and senior management), including discussion on the practices` pros and cons in line with the recommendations of (Voss, 2008). Meetings lasted between two and two and half hours and were held every other week at the company's production premises.

3.6.3. External validity

External validity relates to the general applicability of the conclusions. In other words, to what extent is it is possible to generalize from the data and context of the research study to broader populations and settings (Karlsson, 2009). Yin (2009) distinguishes between two forms of generalization, namely 'statistical generalization' and 'analytical generalization'. Case studies of a qualitative nature relies on analytical generalization, meaning that researchers strive to generalize a particular set of findings to a broader theory. From the perspective of theory-development, the findings presented in this dissertation are therefore analytical rather than statistical, as previously developed theory has been used as a template to compare with empirical results.

Another strategy applied to improve external validity was followed by conducting a replication logic in multiple cases. Furthermore, the application of 'thick descriptions' in case studies can enhance external generalization descriptions' of the context (Bryman and Bell, 2011). Such 'thick descriptions' are given for the case companies that participated in this study, the industry studied, and the process under investigation. Such detailed descriptions enable others to make judgements on whether the research findings are transferable to other situations.

3.6.4. Reliability

Reliability refers to the extent to which a study can be repeated and come to same results (Voss, 2008). The goal is to minimize bias such that the same findings and conclusions could be reached if another researcher replicates the study. Essentially, section 3.4 gives a thorough description of the methods used during the six phases of the overall DSR process. As a more specific example, the methodology chapter in Paper 2 explains in detail the steps followed to develop the concept of lean engineering design. Another example is the use of interview guides and evaluation sheets (e.g., Appendix A and C) giving detailed instructions on how data were collected and analyzed. Such strategies make it possible for future researchers to conduct the study and thereby increase reliability (Yin, 2014). Finally, as previously mentioned, always having multiple authors involved in the research process contributed to a more vivid understanding and could be used as an argument for protecting against bias.

4. Findings

This chapter provides a summary of this dissertation's main findings, which deals with the challenges of executing engineering design and its coordination with other ETO operations. The aim is to investigate how lean thinking can be adapted and applied to improve ETO operations. The findings are presented according to the three RQs that have guided this study.

ETO operations have been described as inherently different from those of traditional (repetitive) production (Amaro et al., 1999, Bertrand and Munstlag, 1993, Braiden et al., 1993, Gosling and Naim, 2009, Hicks et al., 2001, Little et al., 2000, Willner et al., 2016b). This dissertation's scope includes the complexity of ETO operations derived from a set of characteristics (as outlined in Chapter 2) that have crucial implications for the execution of engineering design and its coordination with other ETO operations.

The identified characteristics of ETO operations (e.g., high levels of uncertainty in product and process development, due to a high degree of customization; geographically dispersed engineering design and production; concurrent execution of operations to keep lead times short; a high requirement of tacit knowledge to develop advanced and unique solutions) challenge an efficient execution of engineering design, leading to an unleveled workflow and overburdened engineering resources, which in turn could result in a decreased quality of engineering activities, longer lead times, and higher product development costs (Fiore, 2004, Morgan and Liker, 2006, Ward and Sobek II, 2007). Thus, the aim of RQ1 is to identify how lean thinking can be adapted to the execution of engineering design by leveling its workflow. To enable a deeper understanding of how an unleveled workflow contributes to stoppages in engineering design, to begin with, eight real-world challenges have been identified. Then, relevant lean practices from the established literature have been derived. The main findings are presented in Section 4.1.

Customization and ultimately, value generation are achieved through an iterative process between engineering design and other involved ETO operations. Although inevitable, this iterative process allows much leeway for waste generation, expressed in higher costs, quality defects, and longer lead times (Ballard, 2000c, Bonnier et al., 2015, Freire and Alarcon, 2000, Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002). It is argued that successful coordination of iterative operations depends on integration of the different ETO operations that work concurrently on interdependent activities (Emblemsvåg, 2017, Kjersem and Emblemsvåg, 2014, Mello, 2015), an integration that is lacking in traditional PM (see, e.g., (Emblemsvåg, 2014a, Laufer et al., 2015, Laufer and Tucker, 1987, Oehmen and Steuber, 2012). Accordingly, to begin with, the aim of RQ2 is to study engineering design in current practice to improve the understanding of key wastes due to poor coordination. This is followed by an investigation of how lean thinking can be adapted to improve the coordination of engineering design with other ETO operations. Using a maturity model design method, nine lean enablers have been developed. The main findings are presented in Section 4.2.

The answers to RQ1 and RQ2 have led to the development of 20 practices that enhance the execution of engineering design and nine enablers that improve its coordination with other ETO operations through elements of lean thinking. These practices and enablers serve as the artifactual solution for the DSR process used in this dissertation. Therefore, the aims of RQ3 are to investigate the applicability of lean thinking to ETO operations in general and to evaluate the impact of the proposed artifacts on current practice in particular. The main findings are presented in Section 4.3.

4.1. RQ1. How can lean thinking be adapted to the execution of engineering design?

The following paragraphs start with presenting the eight most frequently cited challenges for poor execution of engineering design that result in unleveled workflow as identified during the empirical work of an in-depth singel case study. As stated previously, an unleveled workflow can lead to stoppages, quality and cost deviations and may cause negative impacts on downstream activites. To allow a deeper understanding of unleveled workflow in engineering design, a selection of quotes and/or phrases from the involved practitioner are added to the presentation of results (4.1.1). A thorough literature review combined with the insights from the single in-depth case study developed this PhD dissertation's first element of the DSR artifact. Namely, a list of 20 lean practices that can assist in overcoming an unleveled engineering design workflow (4.1.2).

4.1.1. Real-world challenges for poor execution of engineering design

Challenge 1 was embedded in the substantial amount of tacit knowledge that was required to solve tasks. Being a small and medium sized company, a handful of key resources were involved in almost all decisions, who typically have been employed in the company for several decades. The overload of such resources could easily lead to long waiting times. As stated by an informant within engineering: "*Sometimes we needed to wait for weeks to get input from the fabrication manager*", as part of the fabrication evaluation process step, which is needed to proceed with drawing a delivery schedule.

Challenge 2 related to large batches of documents, as part of contractual agreements, presented a barrier to workflow. As an example, the general arrangement (GA) drawing package, that includes all drawings of design and production, needed to be delivered to the customer after 15 weeks of signing the purchase order. Such a large batch lead to unleveled workload both at the focal company, but also at the contracting company (customer) as the review of large drawing packages was time consuming. Further it stopped, and in some cases, shortened the flow of proceeding tasks, as one of the respondents explained: "*The customer had three weeks to review the GA, but often we didn't get an answer within the agreed time period. We didn't get more time for completing the contract, if the comments were received late.*"

Challenge 3, a major obstacle for workflow was related to the iterative nature of ETO operations, where customization of products to individual customer requirements was achieved through an iterative process of sharing documents between the engineering company and the customer. Such iteration rounds existed both during the bid process as well as after the contract was signed. As an example, " *an iteration could refer to a design part that includes up to 12 rounds of revisions.*" Different codes were used to track the status of the design (e.g., code 1–approved, code 2–you are allowed to start production, code 3–not approved, code 4–for information only).

Challenge 4 related to the need for external verification. To understand this challenge, it is important to point out that the case company delivered products to the offshore industry which imposed strict rules regarding the verification of design and production method. In practice, the ETO company needed to comply with allowances set by governmental bodies and classification companies and used independent third-party verification companies to assure that designs were in accordance with these compliances. This industry practice may result in additional costs (as verification companies are expensive) and delays, which was reflected in a quote from one of the project managers: "*In order to keep lead times short, designs could be sent to the customer and verification companies simultaneously. "In case that the customer didn't not approve the documents, the 3rd party verification was redundant, and as a consequence money was lost.*"

Challenge 5 derived from unsynchronized efforts between engineering and production that created a barrier of to level the workflow. Welding documents can be used as an example to show the effects of an unsynchronized approach. In order to perform welding, the welder needed a set of documents. Detailed Drawing documents provided needed information in regards to material dimensions, GA drawings showed the location of the welds. Weld Procedure Specification documents provided the welder with instructions on how to conduct the weld, where else Welding Drawings gave information on the number of welds that needed be performed. Welding consumed most of fabrication time and the planning of welding was done by the fabrication manager and foremen, where else the production of welding related documentation was planned and executed by the engineering team based on project plans. Welders expressed their concern as follows: "T*he foreman decideed what welds to be done on a daily basis, based on what was going on in production and which tanks that were accessible. Often we lack the needed documents from the engineering guys."* On the other hand, one of the engineers explained: *"We produced welding documents based on planned* *activities as shown in the project plan. I couldn't see if the documents I produce were needed in production that day, next week or in a month."* In other words, production plans were not shared with engineering. Furthermore, during discussions it was observed that engineers were not aware of the fact that welders needed to access four different documents in order to execute a weld.

Challenge 6 was related to uncertainty in regards to getting the contract or not. The CEO explained it as follows: "*Once we had delivered the bid to the customer, we had no guaranteed time for when and if at all we would get the order."* More importantly, "*requests for bid were received, as the market we worked in, demanded them."* An additional obstacal to predictable workload was that "*the sequence we sent bids, is not the same as we receiveed purchase orders*." In other words, bids were prepared based on existing (ongoing projects) and planned (bids for future projects that have been sent). Once, purchase orders were received, schedules needed to be calculated based on true capacity, reflected in what the head engineer called: *"The projects moved from promising department (sales and bidding) to sorry department (engineering and fabrication)."*

Challenge 7 referred to multiple project-based environment. The company's project could last between 8-15 months and there could be up to 15 projects ongoing at the same time. The same engieers could therefore work on several projects at the same time. Deciding on what to work on, in which sequence and for how long was only loosely defined and lied within an engineer's own work responsibilty to handle. In line with queuing theory, throughput time would increase as the number of tasks in the queue increased, and would increase drastically as the level of utilisation approached its limits.

Finally, *challenge* 8 was related to overutilisation of engineering resources. Data collection indicated that engineers were utilized close to 100 % during busy times, whereelse key resouces (e.g., challenge 1), such as the head of engineering, were utilised 120 % over longer periods of time, posing another challenge for leveled workflow. Hence, this suggested that faulty prioritization of tasks and poor understanding of leveled workflow could result in damaging consequences, such as overutilization of resources leading to overburdening the engineers.

To sum up, Figure 5 illustrates the eight challenges that were found as main contributors for unveleved engineering desing workflow. These challenges set out the foundation for a more thorough investigation of which lean practice should be adapted to the ETO context in order to improve the execution of engineering design.

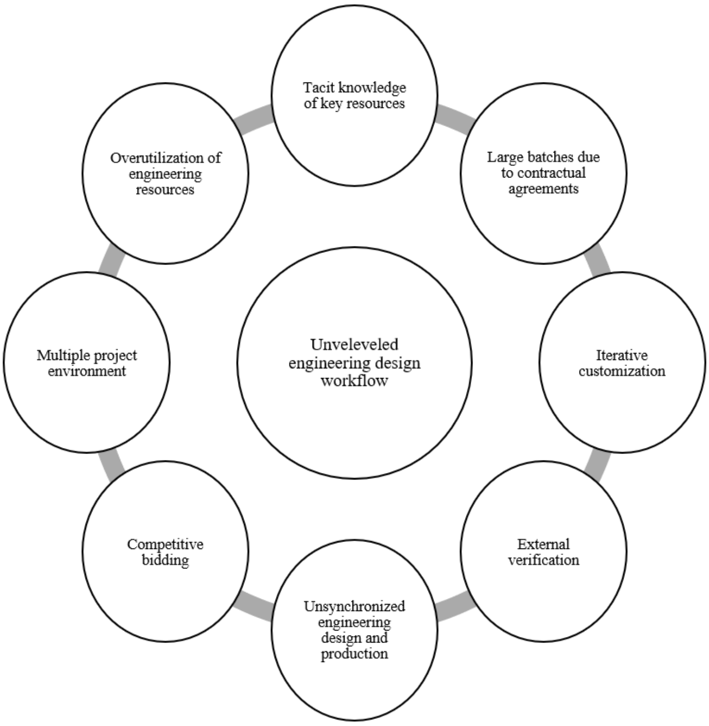


Figure 5. Eight industry challenges that contribute to an unleveled engineering design workflow as observed in engineer-to-order (ETO) operations (from Paper 4)

4.1.2. Lean practices

During the last couple of decades, scholarly journals have published several articles that focus on the content of lean thinking as comprised of lean practices that aim to improve workflow, decrease lead time and enhance overall performance (Deshmukh et al., 2010, Shah and Ward, 2003). For instance, Mirdad and Eseonu (2015) extracted 200 lean practices from 22 studies conducted between 1990s and 2014, while Shah and Ward (2003) identified 22 practices in the literature, which they combined in four bundles when addressing implementation aspects. Though important, these lists of practices refer mainly to production processes with no specific focus on business processes such as engineering design. In contrast, this dissertation is concerned with extracting lean practices specifically focusing on improving the execution of engineering design by levelling engineers' workload and achieving a continuous workflow. As presented in the following paragraphs, a literature study allowed a thematic presentation of individual practices. These are as summarized in Table 6.

One practice often recommended is *takt*. Takt can be illustrated as a heartbeat, where everything moves according to a repetitive rhythm, resulting in a steady workflow. As engineering design work within multiple projects, often compete for same financial, technical and human resources, the issue of uneven resource allocation can emerge. Thus, authors suggest replicating the takt of project launches (Cusumano et al., 1998) where takt regulates how many and what type of new project can be launched. This assists in avoiding overload of resources and unleveled workflow. Hence, every time projects are launched, they are filled with engineering activities, thus practice of takt should therefore be valid and applicable also when assisting engineering workflow (Haque and James-Moore, 2004, Oppenheim, 2004, Ward and Sobek II, 2007). Similar logic is the practice of takt capability, which target the aspects of variabilities during engineering work, i.e., variation in volume and mix, however with an emphasis on fluctuations and capabilities in addition to work capacities (Duggan and Healey, 2016). The idea is to be able to establish different levels of engineering capabilities with regards to variations in both internal and external customer demands. In other words, takt defines how often work needs to be done, while takt capability refers to what competences are required when work is conducted. This helps avoiding minor delays in engineering design along a project to result in large disruptions.

Further, to reduce unleveled workflow, work should be *pulled* not pushed. Pull means that everyone responds directly to customer needs (internal or external) while producing as required and not more. To achieve this Oppenheim (2004) and Ward and Sobek II (2007) introduce the lean practice of standardized integration events, which follows a prescheduled timeline. In this way, it is the events that decides (i.e., pull) when engineering design work is executed, which is different from scheduling work in advance. However, it is critical that each specific event should not be subjected for discussion, but rather handled as a standardized activity were documents and information are passed on, approved and reshuffled if necessary.

The need to sy*nchronize and prioritize* engineering design activities should also be heightened. This is important as some activities might be dependent on a particular resource (e.g., specific engineer skill), stressing actions of prioritized management (León and Farris, 2011). Normally, it is the individual engineer that decides what activity s/he should prioritize, which is important as such decisions indicate freedom and acknowledgement of craftmanship. However, also individuals and teams of engineers are competing among and between themselves for organizational resources, which might result in desynchronized allocation of workload. Thus, there is a need to prioritize the length and sequences of activities to ease the synchronization of workflow. Mascitelli (2007) suggest therefore that teams need clear rules for prioritizing the length and sequence of activities to avoid delays. However, as engineering design is iterative by nature it can trigger new work tasks along an already existing activity/project. Thus to avoid an overload of new activities created by desynchronized teams, Reinertsen (2005) suggests centralized control or single point of initiation, preferably by a lead-engineer. This accentuates the need for re-prioritization, something Liker and Morgan (2019) solves with the practice of periodic progress control. Here, the work-progress is checked and controlled for against prioritized goals. For instance, if engineering design severely deviates from the preplanned status, activities might need re-prioritization to get back on track (Ballard et al., 2002, Tommelein et al., 1999).

Another well-known lean practice aiming to achieve a uninterrupted workflow is called *one-piece-flow*. As revealed by the name, when working in a one-piece-flow mode resources work on one activity at a time. However, this type of work mode is ‘too standardized’ and more suitable in production (e.g., assembly line structure) than in engineering as the latter is embedded in a more ‘organic structure’. To accommodate this, Duggan and Healey (2016) introduce an interesting alternative, called temporary processing cells, where tasks flow in a one-piece manner for a temporary time only. To identify which activities that can be united in a temporary processing cell, one can apply "stacking graphs" where activities with similar process time are gathered. Meaning that each participating engineer can perform activities for e.g., 60 minutes before passing it on to the next step in the temporary processing cell. Hence, a crucial difference between traditional work management and temporary processing cells is that engineers need to shift focus from when a task needs to be finished to when a task will be worked on. This contributes to better synchronization among engineers required effort.

As pointed out earlier, it is difficult to reliably plan the demand of engineering resources, when duration of activities is highly unpredictable. To improve this situation, it is recommended to conduct detailed activity and resource demand *planning*. More precisely, Ballard (2000b) and Tommelein et al. (1999) recommend a backlog of workable activities, which is required to prevent flow interruptions. Thus, a workable backlog of activities that are ready to work on, needs to be planned for, that in case of periods where other activities are put on hold or one is waiting for input from others prevents the workflow from stopping. Beside a workable backlog, two other lean practices were identified that nourish the importance of planning and encounter an unleveled workload. These are responsibility-based planning (e.g., (Ballard, 2014, Emblemsvåg, 2014b) and crew sizing (Tommelein et al., 1999). Both practices emphasize the importance of involving the engineers who will execute the planned activity in the planning process, rather than assigning detailed engineering design activities with clearly defined, non-negotiable deadlines by superiors.

Others raise the issue of large *queues* that are notoriously disliked within the lean literature, as they lead to overload, long lead times and long feed-back loops. To bypass long queues, Reinertsen (1997) suggests applying constrains on batch sizes of work in progress. Although, engineering design work in progress may not be as visible (as e.g., as material in production) and difficult to measure, it has nonetheless an important effect on throughput time. In addition to batch size control, work in progress can be regulated by connecting activities through FIFO-lanes (first-in-first-out) which puts constrains on what to work on first, and how many finished activities can be passed on from one step in the process to the following (Duggan & Healey, 2016). The underlying reason for constraining activities through FIFO rules, is that too many activities waiting in an engineer's inbox causes unnecessary stress, multi-tasking and re-sequencing.

Engineering design work applies a lot of tacit knowledge such as subjective insights, intuitions, or hunches rooted in individual's experience (Nonaka and Tackeuchi, 1995). Although inevitable, tacit knowledge might cause constrains to the flow of work. For instance, experienced engineers might be extensively approached, assigned more work than others because of their expertise and consequently overwhelmed by a huge workload. Instead of relying on few highly experienced key engineers, tacit knowledge neeeds to be transferred, shared, and reused. This accentuates the importance of *knowledge transformation*, Set-based concurrent engineering (Liker and Morgan, 2011), is often highlighted as a strategy for increasing the knowledge transformation rate by considering redundant concepts or design alternatives which allows synthesize learning from weak and strong alternatives. Cross functional teams and conscious overlap of engineering design activities, information flow and responsibilities, have also been recommended as means to achieve reuse of existing knowledge (both tacit and explicit) (León and Farris, 2011, Ward and Sobek II, 2007).

A central element of the lean philosophy is *learning.* To improve the rate of learning, Liker and Morgan (2011) recommend things-gone-wrong meeting. These in-process reflection meetings are cross-functional and have the added advantage that they enable real-time course corrections in addition to process improvement opportunities across different projects. To be successful, these events require a significant level of organizational maturity to create a non-punitive environment where participants have a learning and continuous improvement mind set. Others point at cross-functional communication to enhance learning with the help of 'obeya' (Japanese for large room) where all relevant information is made visible for all project participants (e.g., Nepal et a., 2011).

Many of the aforementioned paragraphs pinpoint at the importance of avoiding delays that contribute to an unleveled workflow. According to Hoppman et al. (2011) and Reinersten (1997) companies should therefore aim to plan their *capacity utilization* carefully. This can be accomplished by employing the rationale behind the classical 'Queuing theory'. From a capacity perspective, it is argued that capacity utilization and queue size have an exponential relationship, meaning that queues and therefore delays will grow exponentially as resources are utilized more. In addition to what was been stated previously regarding constraining work in progress and batch sized, Reinertsen (1997) recommends access to excess resources to increase capacity when needed. As tempting as it seems to utilize precious engineering resources at a maximum the impacts on queues and delays are severe. Therefore, trade-offs between queue size and capacity utilization should be based on economic decisions, where the cost of both is quantified in the same terms.

To add on what has been stated in the previous paragraphs, Liker and Morgan (2011) heightens the philosophy of *systems thinking* as it allows us to understand/observe an organization from a broad perspective that includes overall structures, patterns and cycles in systems. According to (Senge, 2006) systems thinking focuses on how an individual interacts with the system. It does not focus on the individual in an organization, but rather it focuses on the individual's interaction within the organization, like an orchestra. For instance, when engineering design work increases (both with regards to the amount of work and complexities), the firm must invest resources in mechanisms to meet these requirements. Hence, when obvious interventions produce nonobvious consequences, (which often is the case during customer involvement as in ETO operations), there is dynamic complexities that needs to be considered (Senge, 1990). If not accommodated, the high level of utilization can lead to capacity inefficiency, leading to obstacles and delays, and thus requires higher level of knowledge sharing efforts among several engineers to eliminate waste form the system. System thinking can help decreasing such scenarios (Liker and Morgan, 2011).

Table 6. Lean practice that level engineering design workflow (from Paper 4)

Nr	Theme	Lean practice	Objective	Extracted from established knowledge
1	Takt	1.1. Takt of project launches	Managing the launch of new projects through takt can assist in avoiding overload of engineering resources and unleveled workflow.	(Cusumano et al., 1998)
		1.2. Takt within projects	Manage engineering activities through takt can assist in avoiding overload of engineering resources and unleveled workflow.	(Haque and James-Moore, 2004, Oppenheim, 2004, Ward and Sobek II, 2007)
		1.3. Takt capability	Several levels of takt capability allows gearing capacity up and down according to demand, which avoids that small delays lead to bigger delays.	(Duggan and Healey, 2016)
2	Pull	2.1. Integration events	Well organized and standardized integration events keep workflow smooth, as work is pulled rather than pushed.	(Oppenheim, 2004, Ward and Sobek II, 2007)
3	Synchronizing and prioritizing	3.1. Clearly prioritized and synchronized activities	Activities need to be clearly prioritized and synchronized to avoid that everybody decides individually. Teams need clear rules for prioritizing the length and sequence of tasks to avoid delays.	León and Farris, 2011, Mascitelli, 2007)
		3.2. Single point of initiation of tasks	The number of activities in progress and the authority to start new activities needs to be controlled and limited to avoid long throughput times and overload.	(Reinertsen, 2005)
		3.3. Periodic progress control of planned activities	Planned activities need to be checked for progress and if necessary re-planned and re-prioritized, to avoid that the plan loses its validity.	(Ballard et al., 2002, Liker and Morgan, 2019, Tommelein et al., 1999)
4	One-piece flow	4.1. Temporary one-piece-flow-processing cells	Temporary processing cells where engineering design flows in a one-piece-flow manner avoids stoppages and handovers.	(Duggan and Healey, 2016)
5	Planning	5.1. Workable backlog	A workable backlog of activities that is ready to work on, assures a leveled workload in periods where other activities are put on hold or waite for input from others.	(Ballard, 2000a, Tommelein et al., 1999)
		5.2. Responsibility-based planning	Involving the engineer in the planning process allows higher commitment to reach set goals and more reliable plans are achieved.	(Ballard, 2014, Emblemsvåg, 2014b)
		5.3. Crew sizing	Matching needed competence to fulfill planned activities with available resources through crew sizing assists in avoiding delays.	(Tommelein et al., 1999)

6	Queue control	6.1. Constraints on batch size of activity and work in progress (number of activities in progress)	Batch size constrains as well as limitations on the number of on-going activities control throughput time and avoid uneven workload.	Reinertsen, 1997)
		6.2. FIFO lanes between activities	Connecting (value-adding) activities through FIFO (first-in-first-out) lanes putting constrains on how many finished activities can be passed on from one process to the following process. Too many activities waiting in the inbox cause unnecessary stress, multi-tasking, and re-sequencing.	(Duggan and Healey, 2016)
7	Knowledge transformation	7.1. Set-based concurrent engineering	Set-based concurrent engineering increases the learning rate by considering redundant concepts or design alternatives that allows synthesize learning from weak and strong alternatives.	(Liker and Morgan, 2011, Ward and Sobek II, 2007)
		7.2. Conscious overlap of information, activities, and managerial responsibilities	Conscious overlap of information, activities and managerial responsibilities assists in transforming tacit to explicit knowledge.	(Nonaka and Takeuchi, 1995, León and Farris, 2011,
8	Learning	8.1. Cross-functional communication, checklists and obeya	Cross-functional communication, the use of checklists and trade-off curves, obeyas (big rooms) can be used to visualize and standardize the engineering process and allow the transformation of tacit to explicit knowledge.	(Nepal et al., 2011)
		8.2. Things-gone-wrong meetings	In-process reflection events that are cross-functional have the added advantage that they enable real-time course corrections in addition to process improvement opportunities.	(Liker and Morgan, 2011)
9	Systems thinking	9.1. Delaying key decisions to avoid rework	Delay key decisions where possible until more accurate data is at hand to avoid rework at later stages.	(Liker and Morgan, 2011)
10	Capacity utilisation	10.1. Excess resource capacity	Access to excess engineering capacity can be used to avoid small delays that may lead to bigger delays.	Hoppmann et al. 2011, Reinertsen, 1997)
		10.2. Capacity planning	Realistic Capacity planning to avoid high utilization of engineering resources.	(Reinertsen, 1997)

4.2. RQ2: How can lean thinking be adapted to the coordination of engineering design with other ETO operations?

The following paragraphs presents the results of investigating how lean thinking can be adapted to the need of coordinating ETO operations that are executed concurrently (e.g., procurement of long lead items starts prior engineering design is finished) geographically dispersed (e.g., component fabrication is done abroad), and by different organizations (e.g., company that designs the product does not produce it within its own production facilities). To allow a deeper understanding of coordination challenges, key wastes of engineering design were mapped and analyzed in current practice (4.2.1). Following a four-step maturity model design methodology, nine enables were developed, demonstrated, and evaluated in close cooperation with ten ETO companies. These enablers represent this PhD dissertation's second artefactual element. Namely, a list of nine lean enablers that enhance coordination of ETO operations by eliminating wastes (4.2.2).

4.2.1 Key wastes of coordination of ETO operations

In its broadest sense, waste is any activity that absorbs resources but creates no value. First and foremost, the waste of waiting came from waiting for information, calculations, approvals, decisions, and so on. Although waiting was avoidable through better coordination, there was some waiting that was arguably less avoidable. For instance, drawings needed to be sent to independent authorities for approval. These authorities had set processing deadlines. However, case C experienced less waiting for approvals when the same employee of the approval authority was regularly used as a contact person. A key issue here is about the effect of waiting on other wastes, as it is supplemented with the second and the third wastes - over-processing and over-production, respectively.

Second, the waste of over-production was also evident in engineering design. All case companies reported starting activities prior to plan dates, leading to poor coordination and hence the wrong output. While this waste was avoidable, drawings for long lead-time items needed to be released early to assure the project's overall deadline would be met, a risk that ETO companies should take.

Third, over-processing clearly translated well into the ETO context. Compared with traditional production, engineering design is unbounded and adjustable, meaning that both start and end points, determining a project's specification range, can easily be changed. All cases showed examples where the ETO companies extended the specification range, without the customer asking for it. For instance, employees were too creative and gave more than the customer paid for, or the drawings contained more details than necessary. To cite another example, the solutions were based on prior experience and preference, rather than the current specifications. Case C showed over-processing due to a one-fits-all process, meaning regardless of whether the project was supposed to be delivered fast, at low cost or with topmost quality, the task execution approach was always the same. Furthermore, over-processing waste was associated with silo thinking. In case C, senior engineers used their experience as a means of power or a way to come up with solutions to problems at hand, based on a mere gut feeling. Although such decisions could be fruitful and speed up decision processes, they were not based on facts, with too little time was spent on considering the effects on related and downstream activities.

The fourth waste category refers to defects and rework. As shown in previous sections, the time frame of a project, especially the length of iterations, represents itself as an inherent factor in the non-value-adding activities discussed in this study. This is in line with Oehmen and Rebentich's (2010) classification of three waste categorizations derived from what they refer to as time pressure. First, time pressure entices people to take short cuts and ignore established processes and best practices, thus leading to defects. Resorting to quick fixes and patchwork is preferred over finding and fixing error sources. Second, time pressure leads to large information inventories and increases the probability of working on defective or outdated data. Third, besides the psychological effect of stress that elicits errors, time pressure forces people to pass on information that has not been verified or where the person in charge is uncertain about its quality. Although the majority of the case companies agreed on this categorization, case C argued for the opposite, when explaining that the projects with short, allocated time were those that they managed to deliver most efficiently (in terms of quality, profitability, and resource utilization). Furthermore, although changes generate rework, in the

ETO context, allowing changes is part of the business model that outperforms those of more rigid competitors. Additionally, cases A – E showed that a high focus on resource utilization leads to several wastes, including defects. In some cases, the researchers observed engineer utilization of 100%. High utilization was presumably difficult to avoid, especially in small companies.

The fifth and the sixth wastes referred to movement and transportation, respectively. Small and medium sized companies had limited access to engineering capacity. The engineers worked on several projects concurrently, making stop-and-go (switching task and focus) an unavoidable way of working. In case C and I, engineers worked on up to 5 projects at the same time. In other cases, engineering capacity was increased by hiring external engineers. Although extra capacity helped in smoothing out uneven demand, it increased the need for handovers and training, expressed as transportation waste. The lack of system integration also led to manual information transfers and doubling of information. Many of the cases considered the process of generating a plan as wasteful; therefore, it was often neglected. The authors would argue for the contrary. Although things change often, planning is inevitable. The aim is not to produce the ‘perfect’ plan, but to understand the current situation and prepare for the future by identifying possible constraints and solutions.

The seventh waste category expressed itself in the form of inventory. For instance, work in progress increased as designs were not considered or put on hold. As expected, the case analysis showed that waste in engineering design was driven by unleveled workload and inconsistent demand. By failing to balance demand unfair pressures were put on activities and people, as a result causing the creation of surplus inventory and other wastes. Moreover, unleveled workflow causes overburden, expressed as unnecessary stress to employees and processes, triggering wastes, such as defects and movement. An interesting notion is that none of the representatives of the case companies mentioned large information inventory as a potential reason for waste. Advances in data collection and analysis could potentially lead to information inventory overload. This notion confirms the fact that although technology exists, the operationalization of data management technology is still in its infancy. In the future, information accessibility and utilization may allow competitive advantage for organizations;

nevertheless, due to strict contracts, information transfer from one project to others might be restricted.

The eighth and final waste category is that of unused employee creativity. For instance, case A pointed out the lack of transparency of other ongoing activities in the project as a hinderance to utilizing a group's potential capacity for creativity, rationality, and knowledge-storage. To cite another example, some contracts specified a solution but not functionality, resulting in employees that answering merely to the contract and did not engage in finding the best solution.

To sum up, the case analysis shows that waiting, over-production, over-processing, defects, and movements as the most common wastes in engineering design. Table 7 summarizes wastes grouped into categories as defined by Rossi et al. (2017). To allow a deeper understanding of how wastes emerge in engineering design, the table includes a selection of quotes and/or phrases from the interviews.

Table 7. Engineer-To-Order specific wastes as found in engineering design (from Paper 3)

Waste categories as defined by Rossi et al. 2017	**ETO specific examples**	**Empirical evidence (observation / quotation)**
1. Waiting Waiting for work to be completed by a previous process or person.	Waiting for information from external and internal stakeholders. Waiting for successors. Waiting for technical input or decisions.	*1.1. Waiting for information and/ or approval from classification societies, customer and 3rd-party approval companies.* *1.2. Waiting for calculations from other people and departments, such as procurement.* *1.3. Activities are uncoordinated, or planned minimal degree of concurrence and, dependence of activities when planned.*
2. Over-production Producing more, faster, or at an earlier stage than is required by the next process (or customer).	Making calculations and analysis that are unnecessary because of project similarities or too early when information is immature. Over-specifying tolerances. Over-specifying functionality. Keeping busy.	*2.1. Job packages that describe in detail each piece of assembly. This was demanded from one customer and became a habit for all future projects.* *2.2. Mechanical engineering over-specifies functionality to compensate for suppliers' tendency to deliver under agreed tolerance.* *2.3. Over specifying capacities due to earlier projects or an engineer's personal preferences.* *2.4. Starting activities prior to the planned date, which leads to poor coordination and hence wrongful output.*

3. Over-processing Performing unnecessary processing on a task.	Getting too excited. Keeping busy. Stuck in habits. Too detailed purchasing (specifying solutions and not functionality). Silo-thinking. One-fits-all approach.	*3.1. Engineers are too creative and give more than customer wants.* *3.2. Drawings contain too many details.* *3.3. When resources are available, drawings are checked several times.* *3.4. Pre-starting activities prior customer requirements are finalized to save time or use idle capacity.* *3.5. Solutions chosen based on prior experience and preferences, neglecting the specific projects requirements.* *3.6. Specifying purchased components too detailed, instead of using components within approval range as delivered by suppliers.* *3.7. Not analyzing potential impacts on downstream activities, leading to wrong outputs.* *3.8. No matter if the project (task) is supposed to be delivered fast, cheap or with upmost quality – the approach is always the same.*
4. Defects Any kind of correction, such as late engineering changes.	Wrong information. Incomplete information. Mistakes. Rework. Allowing changes. Resource utilization.	*4.1. Delivering wrong drawings due to misunderstanding or lack of coordination.* *4.2. Making assumption due to incomplete customer specifications.* *4.3. Choosing wrong material, sub-components or forget elements.* *4.4. Wrong calculations based on wrong assumption.* *4.5. Correcting wrong information leading to rework, scrapping, revisions and checking.* *4.6. Starting activities too early – quality of information is decreased and needs to be redone.* *4.7. Rework due to changes.*
5. Movement Excess movement or activity during task execution	Stop and go. Bi-lateral working. Wrong in – Wrong out.	*5.1. Sharing same resources on multiple projects leading to stop and go activities and unnecessary 'hand overs' when other resources need to pick up tasks from others.* *5.2. Instead of organizing the work through effective meetings, people meet one on one and make decisions that are not sufficiently discussed in the team.* *5.3. Chasing a plan that is wrong in the first place due to poor updating efforts.*
6. Transportation Movement of documents/information/tasks	Handovers	*6.1. Hiring of external engineers increases training need.* *6.2. Lack of system integration that leads to manual information transfer and doubling of information.*
7. Inventory Building of more information than is needed.	Designs in progress. Early start.	*7.1. Incomplete design due to customer termination.* *7.2. Designs that are not considered.* *7.3. Designs are put on hold because other projects were more urgent.* *7.4. Starting on documents that cannot be completed.*
8. Unused employee creativity Failing to develop and/or utilize human capabilities.	One-fits-all approach. Contracts that specify functionality and not solutions. Lack of transparency.	*8.1. Reusing the same design that worked last time.* *8.2. Employees just answer to a contract and do not engage in finding the best possible solution.* *8.3. Employees do not know enough about the status of other activities which could limit their creativity, rationality and memory.*

4.2.2. Lean enablers

Following a four-step maturity model methodology, a set of nine lean enablers targeting the improvement of poor coordination of engineering design with other ETO operations, were designed and developed. The following paragraphs are structured according to the four steps of maturity model design that were followed.

Step 1: Problem definition

The maturity model (MM) development starts with defining the problem to be addressed.

To begin with, it was important to understand the current approaches used when coordinating ETO operations on a project organizational level. Therefore, following the interview guide (Appendix A), the research team mapped the process in each of the ten case companies (Table 5 in chapter 3) resulting in five common planning and control-related problems as part of coordination, hindering the companies' ability to achieve project goals. The following paragraphs therefore present these problems and highlight some comments on their implications for coordinating ETO operations. It also cites other studies that refer to similar problems.

Keeping the plan updated. Due to the frequent changes and sometimes overwhelming customer involvement throughout the project phases, the plan, capturing all needed efforts by the involved operations, rapidly lost validity if not updated accordingly. Once a plan lost its validity, it was used for formal reporting only (e.g., a milestone report to the customer). The plan document was often stored locally on the project manager's computer and not shared with other project disciplines. The companies used a variety of key performance indicators (KPIs) to track project performance (e.g., number of deviations and number of days delayed compared with the plan). If the plan was not updated according to the changes, all KPIs that measured project performance against the baseline (the original project plan) lost their validity. Although this research argues that plans are important, keeping them updated is even more crucial. Hence, a plan is useful only when it represents realistic activities and is kept valid through sufficient updating. The weakness of outdated overall plans is also acknowledged by APM and Scrum (Adrialdo et al., 2017).

Planning—a neglected competence. All companies expressed their need for improving their planning process because it was often unclear what a plan should include. However, the research team observed that only a few staff members (often with little formal competence or training project planning and control) were dedicated to planning. Project managers were often left alone in drawing and maintaining plans. Moreover, planning personnel was often among the first employees who were laid off or relocated during financial crises such as in 2015 - 2016.

Planning and deciding in isolation. The research team observed that plans and decisions were frequently made in isolation. Individuals (e.g., project lead engineers) often made decisions without consulting other project team members (e.g., fabrication managers). The process of analyzing the impact of new knowledge (in the form of suggestions from engineers, the fabrication staff, or customers) was found to be person dependent, and little training or formalized guidelines were provided. The decisions' effects were also difficult to track and seldom documented for post-project evaluation. For example, changes in detailed designs can have high impacts on subsequent activities, such as production. Drawing up plans without including all participants, such as the person who will actually execute the planned activity (called the last planner in LPS®), leads to unrealistic activities and low commitment and consequently to delays (Ballard, 2000a).

Low level of detailed planning for engineering design. In line with the findings of Little et al. (2000), the research team observed that the level of detail varied among the involved ETO operations. Production plans were often quite detailed, while engineering design plans were less detailed or non-existent, making it difficult to align interdependent activities. This situation is especially true when engineering design and production are carried out concurrently (Mello et al., 2015a).

Neglecting checking and acting on delays. In line with the findings of Adrodegari et al. (2015), ETO companies tended to neglect checking the progress of planned activities, especially evident in engineering design activities, as these activities often are difficult to define exactly or quantify in advance. Many rounds of verification add to the complexity of planning or measuring the progress of engineering design activities. If activities are not checked against the planned progress, no actions are triggered to ensure the resumption of the planned performance. Identifying potential progress delays at a late stage leads to firefighting instead of proactive constraint elimination prior to the scheduled starting date of a planned activity (Ballard, 2000a, Emblemsvåg, 2014b, Emblemsvåg, 2014a).

Step 2: Comparison of existing maturity models (MMs)

Once the problem is identified, the need for a new MM should be demonstrated. The Project Management Institute (Institute, 2013) provided an overview of different MMs. However, many of these models were limited in scope and focus on categorizing an organization's actual behavior. A search for terms such as *maturity model*, *project planning*, *project management*, and *ETO* in the major databases, including Science Direct, Emerald, Pro Quest, and Google Scholar found project management and lean-based literature that dealt with project planning and control issues (see, e.g., (Emblemsvåg, 2017, Emblemsvåg, 2014b, Kjersem and Emblemsvåg, 2014, Mello, 2015) and lean construction literature emphasizing the lack of an effective project planning and control process (see, e.g., (Ballard, 2008, Mossman, 2005, Viana et al., 2017). Other studies investigated the MMs' applicability in ETO operations (see, e.g., (Neff et al., 2014, Nesensohn et al., 2014, Netland and Alfnes, 2011, Willner et al., 2016a). Further contributions applied either capability maturity model or the PMI's project MM as the reference for measurement from an overall project management perspective (see, e.g., (Cooke-Davies and Arzymanow, 2003, Crawford, 2007, Demir and Kocabaş, 2010, Dooley et al., 2001, Gasik, 2011, Grant and Pennypacker, 2006, Holland and Light, 2001, Ibbs and Kwak, 2000, Institute and Project Management, 2013, Jiang et al., 2004, Jørgensen et al., 2007, Kerzner, 2001, Kwak and William, 2000, Maasouman and Demirli, 2016, Netland and Alfnes, 2011, Pennypacker and Grant, 2003, Sarshar et al., 1999, Wendler, 2012).

The research team concluded the literature review by acknowledging the absence of any MM that described and measured the lean project planning and control processes for coordinating ETO operations.

Step 3: Iterative development

As described in the methodology section of this dissertation’s second appended paper, the research team selected an iterative approach for developing the MM. The knowledge gained during the problem identification step, coupled with the insights from the relevant literature, formed the basis for identifying the enablers of lean project planning and control as part of coordination and the levels that would evolve from the process. The initial framework consisted of six enablers and tested at three case companies (see appended Paper 2 for an overview of case companies involved), showing low maturity in regard to the integration of all ETO operations and physical progress measurement. Meetings and information exchange (updating the plan) were not standardized.

In the second round of iterative maturity model development, the research team defined the maturity levels of three case companies by applying the MM. The results, as shown in figure 6, were presented at the annual APMS conference in 2015 (this dissertation's first appended paper).

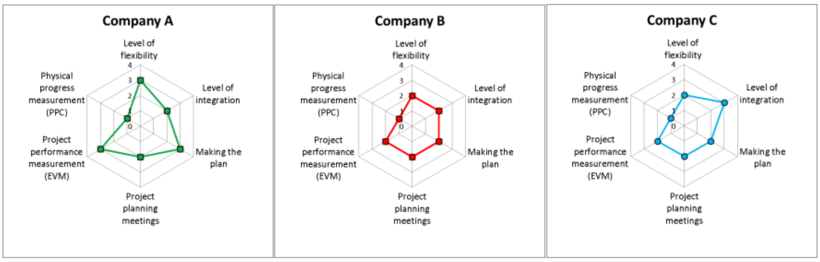


Figure 6. First AS-IS maturity level of the planning and control process of ETO operations (from Paper 1)

During the final round of iteration, the research team refined the model by presenting it to the case companies' representatives and discussing its features with them. This iteration added three enablers—replanning, lessons learned, and impact analysis. Hence, as shown in Table 8, nine enablers can be adapted to improve the coordination of ETO operations. This section presents each of these nine enablers in detail.

Planning flexibility. This assesses the methods for creating a project plan and the level at which the plan is developed. When a plan is made at a higher level in the organization, the people executing the activities may be unable to adjust these to the realities of the project.

Updating the plan and replanning delayed activities as often as needed, while preparing for the next period, demands flexibility in the organization.

Planning integrity. This evaluates the connections between the plans from the different departments and organizations participating in the project. Having a clear overview of the project situation implies a firm integration of all the plans with the main project plan.

Planning commitment. This determines the level of planning by examining who creates the project plan and how it is developed. A project plan that is created through collaboration among all project disciplines generates better communication and deeper commitment within the organization. When the project plan is dictated from a high management level, most of the participants are not offered the possibility to prepare the activities for the next period due to the lack of on-time updated information. Consequently, people involved in the project lack commitment and willingness to get involved in the planning process.

Planning participation. This regulates the number of meetings (whose main agenda items are planning, controlling, and replanning) per project. In some projects, the number of meetings was quite low, or issues that are irrelevant to planning disturb the agenda. A project planning meeting is an important arena for communication and discussion about the project status and the issues to be solved. Involving all discipline coordinators in regular project planning meetings offers everybody the possibility to both be informed about what is occurring in the project and inform the rest of the organization about eventual issues that can affect the project. A project team can thus proactively work toward eliminating any constraints that might affect the project in the next period, as well as ensure that there are enough executable tasks as buffers.

Project dedication. This identifies the tools used by the project team to measure its performance. One of these tools is EVM, a relevant tool for measuring the project's evolution in relation to the planned budget, time, and resources, enabling the management team to take the necessary actions and keep the project on the most favorable path. This tool is mainly useful at the management level.

Planning dedication. This examines the method of reporting the progress of planned activities. The PPC is used as a mode to obtain involvement and commitment from the department or operation coordinators and the other project participants. This tool measures the percentage of activities completed as planned, and it is important to specify that the last planner (discipline coordinators, team leaders, etc.) participates in creating the plans used for measuring the PPC.

Replanning ability. This assesses the method of replanning delayed activities, for example. In some cases, the project organization assumes that people will execute the delayed activities as soon as possible, without considering the consequences of such delays on other activities from other disciplines.

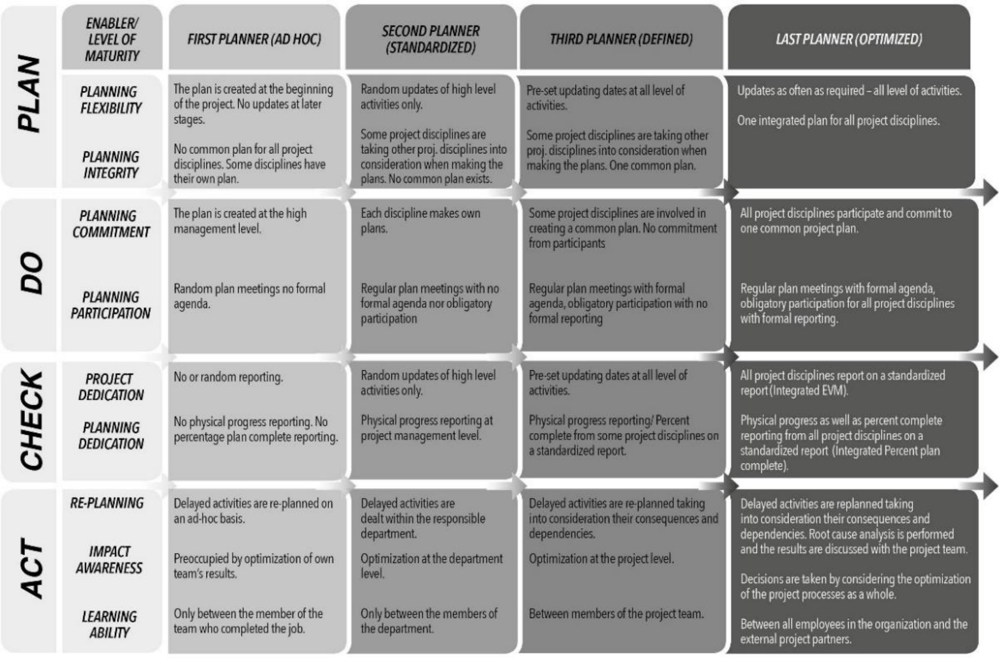
Impact awareness. This evaluates the decision-making process in the project organization and how each department or operation optimizes its own activities without considering the rest of the team. It is essential to consider the bigger picture rather than optimizing individual operations.

Learning ability. Finally, this determines the dissemination of experiences among different projects in the organization and among the project participants. Problems should be made visible to allow learning and improvement for the future.

Table 8. Nine lean enablers for coordinating ETO operations (from Paper 2)

Lean approach	Underlying ruling principles	Lean enabler	Definition
PDCA	Plan - involves the identification, understanding, and analyzing the problem in order to understand the root cause of it and develop a possible solution and an implementation plan. Do - concerns putting the plan into action. Check - the effects of the implementation are measured and compared with the target. Act - two options are possible; either that the success of the implementation is confirmed, or that remedial action needs to be carried out if the solution failed to meet the requirements. Performing the cycle again will improve the knowledge further and can bring us closer to the goal.	Planning Flexibility	Assesses the method for creating, updating and re-planning needed activities to deliver an ETO product.
		Planning Integrity	Evaluates the connections between the plans from the different departments and organizations participating in the project.
		Planning Commitment	Assesses the method for creating a plan of needed activities to deliver an ETO product by examining who creates the plan and how it is developed.
		Planning Participation	Regulates the number of meetings (whose main agenda items are planning, controlling, and replanning) per project.
LPS	Plan in greater detail as you get closer to doing the work. Produce plan collaboratively with those who will do the work. Reveal and remove constraints on planned tasks as a team. Make and secure reliable promises. Learn from what went wrong.	Project Dedication	Identifies the performance measurement tools used by the project team.
LPP	Apply cost performance indicators as par tof EVM in order to measure project performance and progress of a project by comparing the baseline of the project with reported physical results. Equal treatment of people. Apply high meeting discipline, e.g., attendance is required, people need to come prepared.	Planning Dedication	Examines the method of reporting the progress of planned activities.
		Replanning Ability	Assesses the method of replanning delayed activities.
APM / SCRUM	Flexible delivery. Flexible deadlines. Local teams. Frequently revisions. Collaboration. Orientation of interfaces and behavior.	Impact Awareness	Evaluates the decision-making process in ETO operations and how to avoid that each department optimizes its own activities without considering the rest of the team.
TPDS / SBCE	Explore and compare alternative options independently and parallel. Postpone design decisions as long as possible. Generate reusable knowledge. Engage different kind of resources in problem-solving activities. Strive for continuous improvements and continuous learning.	Learning ability	Determines the dissemination of experiences among different projects in the organization and among the project participants.

To understand the transition from traditional to lean planning and control that allows a better coordination of engineering design with other ETO operations, this dissertation distinguishes between four levels of maturity. Following the concept of maturity, the development proceeds from a lower to a higher capability level. The notion of a ladder follows the logic that maturity develops over time, recognizable through certain steps or stages. Inspired by LPS® (Ballard, 2000a), the planning and control capability matures from the first planner (ad hoc process), to the second planner (standardized process), the third planner (defined process), and finally, to the last planner (optimized process). Moving from the lowest level of maturity (*the first planner)* to the highest level (*the last planner*) describes the transformation from top-down planning (where plans are pushed from planners to doers) to a combined bottom-up and top-down approach (pull and push). As the planning and control process of ETO operations matures over time, an organization advances from poor planning in isolation at the first planner level, to the second and the third, finally evolving to the final level of maturity. Figure 7 shows examples of the nine lean enablers for each level of maturity.



	ENABLER/ LEVEL OF MATURITY	FIRST PLANNER (AD HOC)	SECOND PLANNER (STANDARDIZED)	THIRD PLANNER (DEFINED)	LAST PLANNER (OPTIMIZED)
PLAN	PLANNING FLEXIBILITY	The plan is created at the beginning of the project. No updates at later stages.	Random updates of high level activities only.	Pre-set updating dates at all level of activities.	Updates as often as required – all level of activities.
	PLANNING INTEGRITY	No common plan for all project disciplines. Some disciplines have their own plan.	Some project disciplines are taking other proj. disciplines into consideration when making the plans. No common plan exists.	Some project disciplines are taking other proj. disciplines into consideration when making the plans. One common plan.	One integrated plan for all project disciplines.
DO	PLANNING COMMITMENT	The plan is created at the high management level.	Each discipline makes own plans.	Some project disciplines are involved in creating a common plan. No commitment from participants	All project disciplines participate and commit to one common project plan.
	PLANNING PARTICIPATION	Random plan meetings no formal agenda.	Regular plan meetings with no formal agenda nor obligatory participation	Regular plan meetings with formal agenda, obligatory participation with no formal reporting	Regular plan meetings with formal agenda, obligatory participation for all project disciplines with formal reporting.
CHECK	PROJECT DEDICATION	No or random reporting.	Random updates of high level activities only.	Pre-set updating dates at all level of activities.	All project disciplines report on a standardized report (Integrated EVM).
	PLANNING DEDICATION	No physical progress reporting. No percentage plan complete reporting.	Physical progress reporting at project management level.	Physical progress reporting/ Percent complete from some project disciplines on a standardized report.	Physical progress as well as percent complete reporting from all project disciplines on a standardized report (Integrated Percent plan complete).
ACT	RE-PLANNING	Delayed activities are re-planned on an ad-hoc basis.	Delayed activities are dealt within the responsible department.	Delayed activities are re-planned taking into consideration their consequences and dependencies.	Delayed activities are replanned taking into consideration their consequences and dependencies. Root cause analysis is performed and the results are discussed with the project team.
	IMPACT AWARENESS	Preoccupied by optimization of own team's results.	Optimization at the department level.	Optimization at the project level.	Decisions are taken by considering the optimization of the project processes as a whole.
	LEARNING ABILITY	Only between the member of the team who completed the job.	Only between the members of the department.	Between members of the project team.	Between all employees in the organization and the external project partners.

Figure 7. Maturity model for coordinating ETO operations applying nine lean enablers (from Paper 2)

Step 4: Validation

The twofold validation step started with applying the proposed maturity model in seven additional ETO companies (see appended Paper 2 for an overview of case companies involved). The project participants, such as lead engineers, project leaders, and project planners (if available), set scores on a scale of one to four (representing the levels of maturity) as presented in Table 9. The final column (Av.) shows the average of all companies.

The results show a low level of maturity for many of the nine enablers. Except for one company, none scored higher than 2.5 in any of the evaluated enablers. Only two companies used tools, such as EVM or PPC. All companies scored slightly higher in planning flexibility though the plans were still drawn at an early stage and updated randomly at a high level only. ComB clearly stood out and was deliberately included in the sample to show high maturity. The project team of ComB that conducted this assessment had undergone intensive training and implementation of LPP, resulting in an average score of 3.15. The findings showed a low level of lean planning and control maturity, supporting both previous research (see e.g., (Adrodegari et al., 2015, Emblemsvåg, 2017, Koskela and Howell, 2002, Little et al., 2000) and the empirical evidence that laid the foundation for this research. All case study participants agreed that the nine enablers were important for the successful coordination of ETO operations. They also acknowledged that different maturity levels were achievable and that the measurements were realistic (see Paper2).

Table 9. Level of maturity of coordinating engineer-to-order (ETO) operations in ten case companies (from Paper 2)

Planning element	**Com A**	**Com B**	**Com C**	**Com D**	**Com E**	**Co mF**	**Com G**	**Com H**	**Com I**	**Com J**	**Av**
Planning flexibility	2	3	2	2	2	3	2	1.5	2	2	2.1
Planning integrity	2	3.5	1	2	2	2.5	2	1.5	1	2	1.9
Planning commitment	1	3.5	1,5	2	2	3	2.5	2	1.5	2	2.1
Planning participation	2	4	1	1	2	3	1.5	1.5	1	2	1.9
Performance dedication	1	4	1	1	1	2	1	1	1	1	1.4
Planning dedication	1	4	1	1	1	2	1	1	1	1	1.4
Re-planning ability	1	3.5	2	2	2	2.5	2	1.5	2	2.5	2.1
Impact awareness	2	3.5	2	1.5	2	2	2	1.5	1.5	2	2
Learning ability	1	2.5	1	1	2	2	2.5	1.5	1.5	1.5	1.6
Average	1.3	3.15	1.25	1.35	1.6	2.2	1.65	1.3	1.25	1.6	

4.3. RQ3: How applicable is lean thinking to engineering design?

This section presents the main findings of investigating how the proposed artifacts (20 lean practices that target to improve engineering design by levelling workflow and lean enablers that target to improve the coordination of engineering design with other ETO operations by eliminating wastes) can applied be to ETO operations to improve performance. Evaluating the fitness of the proposeed artifactual solutions is an important step in DSR. The following paragraph starts with presenting how the proposed lean practices can be applied in order to reduce engineering desing related challenges that lead to unleveled workflow (4.3.1.) Then, the impact of the proposed lean enablers on key wastes are presented (4.3.2.).

4.3.1. Impact of lean practices on engineering design related challenges

Table 10 shows how the reccommended lean practices (as presetned in section 4.1.2) impact real world ETO challenges (as presented in section 4.1.1). In other words, the table maps the real world challenges identified from the in-depth singel case study against lean practices as found in literature. The potential links are indicated by darker blocks, which signify a strong linkage between challenge and lean practice. The lighter shaded blocks show moderate links between the two, while white blocks indicate a weak or no linkeage between challenge and lean practice. The right collumn summarizes linkages observed and show a number ranging from 3 to 13. Lean practices under the theme of planning (with 13 linkages, 7 strong and 6 moderate) appeared to have the most comprehensive applicability to the real-world ETO challenges, followed by the themes of prioritizing and synchronizing (11 linkages, 6 strong and 5 moderate), and capacity utilization (10 linkages, 4 strong and 6 moderate).

Table 10. Linkage between lean practices and challenges (from Paper 4)

Lean practices	Real world challenge	Tacit knowledge at key resources	Large batches	Iterative customization	External verification	Competitive bidding	Unsynchronized engineering & fabrication	Multiple project-based environment	Concurrent procurement, engineering & fabrication		Sum of linkages found per lean practice theme.
Takt	1.1 Takt of project launches		▨			■		■		■ = 3 ▨ = 2	5
	1.2 Takt within projects			▨				■			
	1.3 Takt capability	▨	▨			■		▨			
Pull	2.1 Integration events	■	■	▨	▨		▨	▨	▨	■ = 2 ▨ = 5	7
Synchronizing and prioritizing	3.1 Prioritized and synchronized			▨	▨		■			■ = 6 ▨ = 5	11
	3.2 Single point of initiation	▨					■	▨	■		
	3.3 Periodic progress control			▨			■	■	■		
One-piece flow	4.1 Temporary processing cells	▨	■	▨			■	■	■	■ = 4 ▨ = 2	6
Planning	5.1 Workable backlog			▨			■	■	▨	■ = 7 ▨ = 6	13
	5.2 Responsibility-based planning		▨		■	▨	■	■	▨		
	5.3 Crew sizing	■					▨	■			
Queue control	6.1 Batch size control		■				▨			■ = 3 ▨ = 1	4
	6.2 FIFO-lanes	■					■				
Knowledge transformation	7.1 Set-based concurrent engineering			■				▨		■ = 2 ▨ = 4	6
	7.2 Conscious overlap	■		▨			▨	▨			
Learning	8.1 Cross functional communication	■						■		■ = 4 ▨ = 2	6
	8.2 Thing-gone-wrong meetings	■					▨	■	▨		
Systems-thinking	9.1 Delaying key decisions						■	▨	■	■ = 2 ▨ = 1	3
Capacity utilization	10.1 Excess resource capacity	▨				■		■		■ = 4 ▨ = 6	10
	10.2 Capacity planning	■				▨		▨			

Strong linkage	■
Moderate linkage	▨
Weak / no linkage	□

Engineering design has been proven to be packed with activities outside a leveled workflow resulting in stoppages and quality issues. There are several important lessons that can be learned from the case study, as companies transform engineering design into a leaner approach:

- First, some lean practices translate better than others into ETO operations. Supported by previous research, e.g., Albert et al., 2017 and Andersen et al., 2007, lean practices grouped under the theme planning had the strongest link between the practice and real-world challenges, followed by the themes of synchronizing and prioritizing, and capacity utilization.
- Second, individual lean practices enhanced other practices. As an example, periodic process control assisted in enhancing capacity planning as it provided an updated status of ongoing activities.
- Third, implementing lean practices requires learning through experiments, similar to findings of e.g., Ballard, 2008. As an example, when the case company tried to separate non-core from core activities as part of setting temporary one-piece processing cells, it started with assigning tasks that were conducted by engineers, first to sales personnel, but later found it more appropriate to place these activities under the responsibility of procurement.
- Fourth, lean thinking does not have to be implemented at a full-scale. This is important lesson learned for small and medium sized engineering companies, which this dissertation is target at. Small and medium sized companies can start at small and defined areas that the company is willing or needing to change and later escalate lean thinking practices to other areas.
- Fifth, value creation within engineering design was made visible. The case company, a typical mechanical engineering company, shifted its focus from creating value solely by producing physical products (e.g., welding pressure vessels) to creating value also through engineering design. This shift in focus brought forward the mutual dependency of engineering design and production and allows decisions that benefit the entire organization. This lesson learned is in alignment with findings from e.g., Bonnier et al., 2015.

- Finally, commitment from top management is unprecedented. The case company's CEO had a strategic commitment to employ lean thinking which is unprecedented when engaging in a lean transformation. This is an interesting addition to the findings of Netland et al., 2016 that found that commitment form top management was a critical success factor when implementing lean in production.

4.3.2. Impact of lean enablers on key wastes of coordination

By integrating evidence from the literature, interviews, workshops, and discussions with experts in the field, this study gains both conceptual and empirical insights in assessing to what extent the lean enablers contribute to improve performance of ETO operations by minimizing the observed key wastes in engineering design. To illustrate these findings, Table 11 presents the overall assessment of the case companies' opinions and experiences regarding the impacts of lean enablers. The left column includes the waste examples as found in the engineering design derived from the cases, while the top row includes the nine lean enablers. The score is calculated by multiplying the ease of implementing the enabler (ranging from 1 = hard to implement to 5 = is easy to implement) with the impact of the enabler on the observed waste (ranging from 1 = low impact to 5 = high impact on waste). The product of probability (i.e., ease of implementation) and impact on reducing waste generates a score between 1 and 25, enabling the analysis to rank the chosen approaches. The consideration of both impact on waste and ease of implementation, allows the creation of a risk-based approach to implementing lean enablers. The enabler with the highest score (risk) will have the highest probability of reducing waste and vice versa. In the context of this study, this risk-based approach can offer several implications for managers implementing lean thinking in ETO operations. These implications will be discussed in the paragraphs following Table 11.

Table 11: ETO waste and lean enablers showing their probability of waste elimination (from Paper 3)

ETO waste examples / 9 lean enablers ***Score= ease of implementation x impact of reduction on waste***	Planning participation	Planning dedication	Re-planning ability	Planning integration	Project dedication	Impact awareness	Learning ability	Planning commitment	Planning flexibility
Sum	**488**	**248**	**234**	**228**	**200**	**194**	**180**	**180**	**159**
1.1 Waiting for information and/ or approval from classification societies, customer, and 3rd-party companies.	12	4	3	4	12	2	2	2	6
1.2 Waiting for calculations from other people and departments, such as procurement.	20	12	3	10	12	10	2	2	3
1.3 Activities are uncoordinated, or planned with minimal degree of concurrence and dependence of activities when planned	20	12	15	10	4	6	6	10	12
2.1 Job packages that describe in detail each piece of assembly, demanded form one customer and became a habit for all future projects.	12	4	3	8	8	6	6	4	3
2.2 Mechanical engineering over-specifies functionality to compensate for suppliers' tendency to deliver under agreed tolerance.	12	4	3	10	4	8	6	6	3
2.3 Over specifying capacities due to earlier projects or an engineer's personal preferences.	16	4	6	10	12	8	10	6	3
2.4 Starting activities prior to the planned date, which leads to poor coordination and hence wrongful output	12	20	9	10	8	6	6	10	9
3.1 Engineers are too creative and give more than customer wants.	12	16	3	10	4	10	4	2	3
3.2 Drawings contain too many details	12	4	3	10	4	10	4	2	3
3.3 When resources are available, drawings are checked several times.	12	12	3	4	4	4	4	2	3
3.4 Pre-starting activities prior customer requirements are finalized to save time or use idle capacity.	12	4	3	4	8	6	4	8	3
3.5 Solutions chosen based on prior experience and preferences, neglecting the specific projects requirements.	16	8	3	8	4	8	10	8	3

3.6 Specifying purchased components too detailed, instead of using components within approval range as delivered by suppliers.	12	4	3	8	4	10	6	4	3
3.7 Not analyzing potential impacts on downstream activities, leading to wrong outputs.	16	4	9	10	20	10	10	10	3
3.8 No matter if the project (task) is supposed to be delivered fast, cheap or with upmost quality – the approach is always the same.	12	4	3	6	12	6	10	4	3
4.1 Delivering wrong drawings due to misunderstanding or lack of coordination	20	8	3	10	4	8	10	6	3
4.2 Making assumption due to incomplete customer specifications.	20	8	12	4	4	4	4	4	3
4.3 Choosing wrong material, components or forget elements.	16	4	12	8	4	8	4	6	3
4.4 Wrong calculations based on wrong assumption.	16	4	12	8	4	6	2	6	3
4.5 Correcting wrong information leading to rework, scrapping, revisions and check	12	4	15	10	4	4	2	6	6
4.6 Starting activities too early – quality of information is decreased and needs to be redone.	12	8	9	6	4	4	2	6	3
4.7 Rework due to changes.	12	4	12	4	4	4	2	4	12
5.1 Sharing same resources on multiple projects leading to stop and go activities and unnecessary 'hand overs'	20	4	3	6	8	6	8	8	6
5.2 Instead of organizing the work through effective meetings, people meet one on one and make decisions that are not sufficiently discussed in the team.	20	8	9	6	4	6	8	10	6
5.3 Chasing a plan that is wrong in the first place due to poor updating efforts.	20	16	15	8	4	4	4	8	15
6.1 Hiring of external engineers increases training need.	8	4	3	2	4	2	2	2	3
6.2 Lack of system integration which leads to manual information transfer and doubling of information.	20	8	15	10	4	6	8	6	12
7.1 Incomplete design due to customer termination.	4	4	3	2	4	2	2	2	3
7.2 Designs that are not considered	16	4	3	2	4	2	2	2	3

7.3 Designs are put on hold, because other projects are more urgent.	12	4	3	2	4	2	6	8	3
7.4 Starting on documents that cannot be completed.	12	12	9	4	4	2	4	2	3
8.1 Reusing the same design that worked last time.	8	4	3	2	4	2	8	2	3
8.2 Employees answer to a contract and do not engage in finding the best possible solution.	12	4	6	2	4	6	6	4	3
8.3 Employees do not know enough about the status of other activities which could limit their creativity, rationality, and memory.	20	20	15	10	4	6	6	8	3

Referring to the findings in section 4.3., the case analysis provided reasons to argue that waste was related to uncoordinated efforts of designers, developers, engineers, employees engaged in engineering design, procurement, production, and so on. As this may not be different for similar project-based environments, such as construction or software development, several possible explanations of wastes related to poor coordination can be found by synthesizing the waste discovered with ETO-specific characteristics. For example, ETO operations were often undertaken by many partners separated by geographical distance (Dubois and Gadde, 2000), meaning that the process of development, production and final assembly could be done in different parts of the world, which could easily lead to misunderstandings, the extra need for coordination or even rework. Second, the ETO products in this case study were mainly maritime items, where technical drawings had to obtain independent, third-party approval, leading to non-value-adding-but-necessary-waiting. Third, once production had fully started, engineering personnel had been assigned to new/other projects, making wastes related to waiting and rework evident.

The involved researchers have encountered several case companies with a low level of willingness to systematically measure waste in engineering design, which could possibly be related to the engineers' perception of systematic waste control that could jeopardize their professional freedom to exercise creativity. Furthermore, some of the wastes were highly person dependent and affected by the employees' prior experience or type of educational background (Emblemsvåg, 2017), influencing their choices on how to develop a design, how to interpret a customer's specifications, or the level of involvement with others when making decisions. It is also important to acknowledge that the presented list of wastes is not exhaustive. Finally, the ETO-specific examples derived from the case study were not exclusive to one waste category but were placed in the most evident category to avoid duplication and increase readability.

The analysis showed how each enabler assisted in eliminating waste. This section presents the lessons learned, following the sequence of the highest to the lowest ranked lean enabler regarding the probability of reducing waste (according to Table 11).

Planning participation: This enabler scores the highest (488), meaning that it has the highest impact on reducing waste and is considered easier to implement than other enablers (e.g., planning commitment and impact awareness). This enabler regulates the frequency of holding and participating in planning meetings. During the planning meetings, all information from all departments (internally and externally) meets the customer requirements and the as-is world. Importantly, these meetings need to be tailored to each project. Too loosely structured meetings can easily be time consuming and ineffective (Kjersem, 2020). The meeting is not over until the participants agree on what to do, leading to more realistically planned activities and thus contributing to reducing waste (e.g., 1.2. Waiting for calculation from other departments, and 8.3. Limited employee capacity and creativity). This view is consistent with that of AL-Qahtani and El Aziz (2013), who mention that unless a collaborative and encouraging environment is established, knowledge will not improve product development capability.

Planning dedication: This enabler assists in keeping track of actual progress. In earlier studies on ETO companies, Adrodegari et al. (2015) have found that the act of monitoring and measuring actual progress versus planned progress is a neglected practice in engineering. Only by knowing where a project team is in relation to where it should be, it can adjust its activities for the next period. The measurement of the percentage of activities completed as planned can act as a motivator for involvement and commitment to assisting in minimizing wastes (e.g., 2.4. Activities are started prior to the planned date, which leads to poor coordination and hence wrongful output).

Re-planning ability: This enabler refers to the routines for re-planning activities. When new activities occur (e.g., due to changes or defects), planned activities need to be replanned, including considering the consequences of such changes or delays for other activities from other disciplines. As such, this enabler is considered to reduce waste (e.g., 1.3 Uncoordinated activities that are planned with minimal degree of concurrence and dependence when planned; and 4.5. Waste related to correcting wrong information, leading to rework, scrapping, additional revisions and controls). In other words, planning should be connected to checking and acting, meaning that only if the status of planned activities is checked, and re-planned when necessary, can realistic progress be achieved.

Planning integration: This enabler incorporates all project disciplines into one common plan and is regarded as having a very high impact on waste reduction (with a total score of 228), although difficult to implement (with a score of 2). Despite the importance of integration, none of the participating companies has systems in place that integrated plans from all disciplines. A possible reason for this is the fact that an ETO company consists of many different disciplines from both internal and external departments, challenging the sharing and integration of plans. Production plans are often quite detailed, while design and engineering plans are less detailed or non-existent, making it difficult to align interdependent activities. This situation is especially disastrous when engineering and production are carried out concurrently (Mello et al., 2015a). Therefore, this enabler recommends establishing routines for integrating plans from all disciplines. Regarding new, project-specific participants, possible integrations need to be identified in the beginning of the project. Furthermore, the case analysis finds it preferable to start sharing available plans, even if they are in a wrong format (need manual adjustment) or are based on estimates (need updates). Incremental improvements make integration easier and shared data more updated over time. Therefore, planning integration assists ETO companies in reducing wastes (e.g., 3.2. Drawings contain too many details, 2.3. Over-specifying capacities, 4.1. Delivery of wrong drawings, and 7.2. Manual information transfer and/or doubling of information).

Project dedication: This enabler refers to the method used by the project team to track its performance. The empirical data show that the most used tool for measuring project performance is earned value management (EVM), which measures the project's evolution in relation to the planned budget, time and resources. While EVM provides top management with a useful early indication of how the project's overall performance, planning dedication and replanning should be taken care of to avoid EVM's measurement of activities that do not give value to the project and are rather wasteful. Combining these three enablers called an integrated EVM system. It means that all disciplines measure progress on both an overall project level (EVM) and on a discipline level, considering how planned activities and actual performance impact affect other disciplines' activities. Hence, as confirmed by the analysis, the enabler project dedication reduces the likelihood of some wastes (e.g., 3.7. Wrong output due to a lack of analysis of impacts on downstream activities).

Impact awareness: This enabler evaluates the decision-making process in ETO operations and how each discipline or department optimizes its own activities without considering the rest of the project team. In ETO projects, many decisions need to be made based on incomplete information; therefore, including all disciplines when estimating the potential impact is recommended. This will raise awareness of the possible outcomes and prepare participants to act accordingly. Furthermore, necessary changes in contracts or agreements can be discussed proactively. Consequently, this enabler is considered to reduce waiting, (e.g., 1.2. Waiting for calculations) and over-processing (e.g., 6.3. Too specific details on purchased components).

Learning ability: This enabler focuses on sharing learned lessons among all employees and external stakeholders (e.g., customers and suppliers) and affects many waste categories, particularly over-processing and overproduction. Elaboration on what succeeds and what fails lies at the heart of lean practices because only in this way can continuous improvement be possible. At the same time, establishing routines for sharing problems, root causes and anticipated solutions among all project participants is difficult, resulting in an ease of implementation score of 2. It is important to focus on reflection and learning, not putting the blame on somebody.

Planning commitment: This enabler refers to the method of creating an initial project plan, including the needed activities to deliver an ETO product. ETO companies need to involve the *doers of each activity* when planning. When plans are drawn without including all participants, such as the person who will actually execute a planned activity, unrealistic activities will be defined and backed up with low commitment, making delays unavoidable. On the contrary, this enabler reduces some wastes (e.g., 2.4. Defects due to starting activities earlier than planned and 6.2. Additional handovers and movement due to ineffective meetings and unsynchronized decisions).

Planning flexibility: This enabler regulates the method of updating the project plan. ETO products are known for the customer's early and ongoing involvement, resulting in many changes throughout the entire project period. Hence, creating and updating the plan as often as needed, while preparing for the next period, demands flexibility in the planning process. Moreover, a well-functioning updating method ensures that the planned activities remain valid according to stakeholder requirements. Therefore, it is recommended that companies establish routines for updating the project plan and visualizing the planned activities. Only if the plan is updated and shows a true picture of the situation would project participants use it and commit to it. Dedicated resources need to be established and trained. Hence, this enabler reduces the probability of some wastes (e.g., 4.5. Unnecessary rework and 6.3. Chasing a plan that is wrong in the first place. This view is consistent with the finding of Ward and Sobek II (2007) and Womack and Jones (1996) that information is only valuable if useful; valuable information reduces the risk of producing an unsatisfactory product or performing a superfluous development activity.

5. Discussion

This chapter discusses this study's findings. To achieve the aim of this dissertation, this chapter proposes how lean thinking can be applied to ETO operations. Guided by the RQs, this chapter discusses (1) how to adapt lean thinking to engineering design, (2) its applicability to engineering design, and (3) how the proposed concept of *lean engineering design* addresses the typical characteristics of ETO operations.

As previously stated, lean thinking is an improvement philosophy, which focuses on the fulfillment of customer value and waste reduction. Lean thinking covers every aspect of an organization (Ballé et al., 2017) and needs to be carefully adapted to the context applied in order to avoid the creation of the so-called "candidate solution" (Gosling et al., 2015). In other words, there is a need for more research that aims to respond to this concern by incorporating reality with theory using a case study approach (León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011). As such, this dissertation aims to bridge the research gaps regarding the need for adapting lean thinking to engineering design, as well as for conducting more empirical case studies, which are scarce in the extant BOK (León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011).

To address the aforementioned gaps, three RQs have guided this study, as illustrated in Figure 8. Accordingly, RQ1 asks how lean thinking can be adapted to the execution of engineering design. RQ2 asks how lean thinking can be adapted to the process of coordinating engineering design with other operations, such as procurement and production. RQ3 asks how applicable lean thinking is to engineering design.

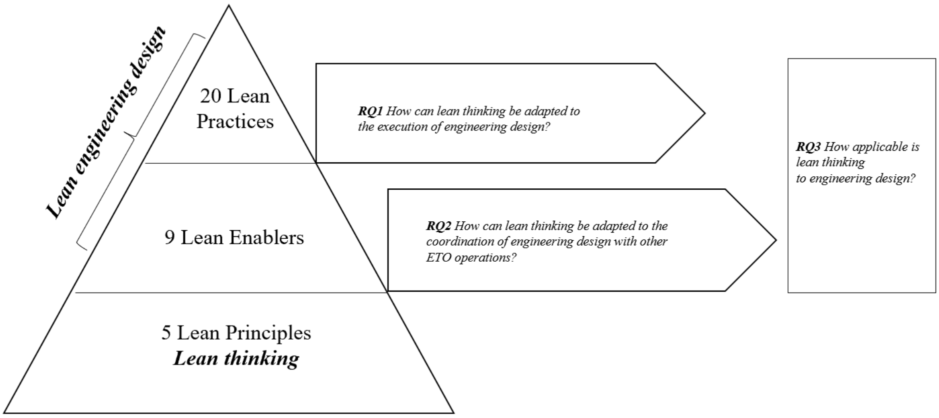


Figure 8. Lean thinking in engineer-to-order operations

Next, Section 5.1 summarizes how lean thinking needs to be adapted to the engineering design context. It is worth mentioning that Section 5.1 summarizes the key findings about both RQ1 and RQ2, while Section 5.2 summarizes those addressing RQ3. Starting from the key findings, the concept of *lean engineering design* is proposed, which is discussed in Section 5.3.

5.1. How can lean thinking be adapted to engineering design?

To begin with, RQ1 asked how lean thinking can be adapted to the execution of engineering design. Through a single in-depth case study, the execution of engineering design in practice was examined, which allowed the identification of context-specific characteristics that challenged this process. The study found a total of eight real-world challenges that frequently led to an unleveled workflow. Unleveled workflow was unwanted as it resulted in overburdened engineering resources, quality deficiency, and lead-time delays. Once the context to which lean thinking should be applied was analyzed, a literature review of lean practices resulted in a list of 20 practices that could potentially be adapted to engineering design.

Similarly, RQ2 asked how lean thinking can be adapted to the process of coordinating engineering design with other operations, such as procurement and production. To begin with, an extensive multiple case study of 10 ETO companies mapped and analyzed current practices to gain a thorough understanding of the context to which lean thinking would be applied. The study identified an extensive list of wastes that indicated how iterative engineering design caused wasteful activities while interacting with other interdependent and overlapping operations. Following a maturity model design method resulted in nine lean enablers that could potentially be adapted to the coordination of ETO operations.

As such, the aforementioned findings contribute to bridging the first and the second research gaps:

- More research is needed to investigate how lean thinking needs to be adapted to new contexts, in addition to covering the need for more in-depth case studies.
- More research is needed to investigate engineering design in practice, which will allow a discussion on how its inefficient execution and coordination create waste.

5.2. How applicable is lean thinking to engineering design in ETO operations?

Research suggests that lean thinking allows comprehensive improvements regarding shorter development times, lower costs, and less resource requirements (Beauregard et al., 2011, Hoppmann et al., 2011, León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011, Nepal et al., 2011). However, more research is needed to increase the understanding about applicability, that is, how well lean thinking is suited for improving the process of engineering design, as found in ETO operations (Alderman et al., 2001, Birkie and Trucco, 2016, Black, 2007, Emblemsvåg, 2017, 2020, Hoss and Schwengber ten Caten, 2013, Jasti and Kodali, 2015, Johansson and Osterman, 2017, Towill, 2007, Viana et al., 2014, Yadav et al., 2019).

Therefore, RQ3 investigated the applicability of lean thinking to ETO operations and evaluated the impact of the proposed lean practices on the execution of engineering design and the impact of lean enablers on the coordination of ETO operations in particular.

Regarding lean practices, the study found that all 20 practices had some linkage to the observed challenges. In other words, any practice applied could lead to potential improvement in leveling workflow. This was not surprising as the practices were selected carefully from the relevant lean thinking theory. It means that the practices were taken from project-based environments, such as LPD and lean construction, where they had been proven to be applicable. As such, the findings support the recommendations of Gosling et al. (2015) regarding contextualization. However, the practices grouped under the theme planning appeared to have the most comprehensive applicability to real-world challenges, followed by the themes of prioritizing and synchronizing and capacity utilization (10 linkages: 4 strong and 6 moderate). Overall, important lessons were drawn that ETO companies could learn from, including the following: Lean thinking did not have to be implemented on a full scale to begin with. Value creation in engineering design could be made visible. Commitment from top management was unprecedented.

Regarding lean enablers, the study found that coordination was not only about optimizing (or balancing) the available resources, the desired quality, or the available time by setting up the activities that need to be done. It was as much about formulating a strategy of collecting and analyzing the knowledge and information available to make the right decisions. As new knowledge became available or changes were requested, planned activities and available resources needed to be reallocated. More project participants implied more information that led to a higher probability of changes or adjustments, making the need for coordination even more evident. This situation was certainly true for ETO companies because they involved many individual yet interdependent participants demanding frequent changes and adjustments; therefore, the lean enablers were tailored to meet this need of ETO operations.

It is important to point out that the nine lean enablers mostly relate to how people participate in coordinating ETO operations (e.g., how to plan activities, how to urge participants to commit to planned activities, who participates in project meetings, how to make decisions). The reason behind this choice was that the research team observed that no matter what kind of information technology system was used by the case companies to undertake their projects, the process of gathering the data, involving people, and obtaining their commitment prevented the project team from functioning properly.

All case study participants agreed that the nine enablers were important for successful coordination of ETO operations. They also acknowledged that different maturity levels were achievable and that the measurements were realistic. Moreover, many of the enablers had a positive impact on reducing wastes.

It is crucial to state that the involved researchers have encountered several case companies with a low level of willingness to systematically measure waste in engineering design, which could possibly be related to the engineers' perception of systematic waste control that could jeopardize their professional freedom to exercise creativity (Dixon, 1989, Penny, 1970, Ulrich and Seering, 2002, Wallace and Hales, 1987, Winner et al., 1988). Furthermore, some of the wastes were highly person dependent and affected by the employees' prior experience, type of educational background (Emblemsvåg, 2017)—influencing their choices on how to develop a design and how to interpret a customer's specifications—or level of involvement with others when making decisions. Hopefully, this dissertation's findings and recommendations have contributed to increasing the understanding of the rationale behind the efforts of identifying, defining, and minimizing waste in engineering design, based on the following assumption: if companies are able to identify the types of waste they generate, then they can find a way to remove those wastes by using lean enablers, and by doing so, gain a competitive advantage (Ohno, 1988). For this reason, the proposed lean enablers allow ETO companies to gather, discuss, evaluate, and eventually transform information into value. As a result, knowledge gaps are identified and filled at an early stage (Liker and Morgan, 2019). Although applying the lean enablers may require operational adjustments and potential increases in short-term costs, the long-term benefits are most promising.

As such, the aforementioned findings contribute to bridging the third research gap:

- More research is needed to increase the understanding about the applicability of lean thinking to ETO operations.

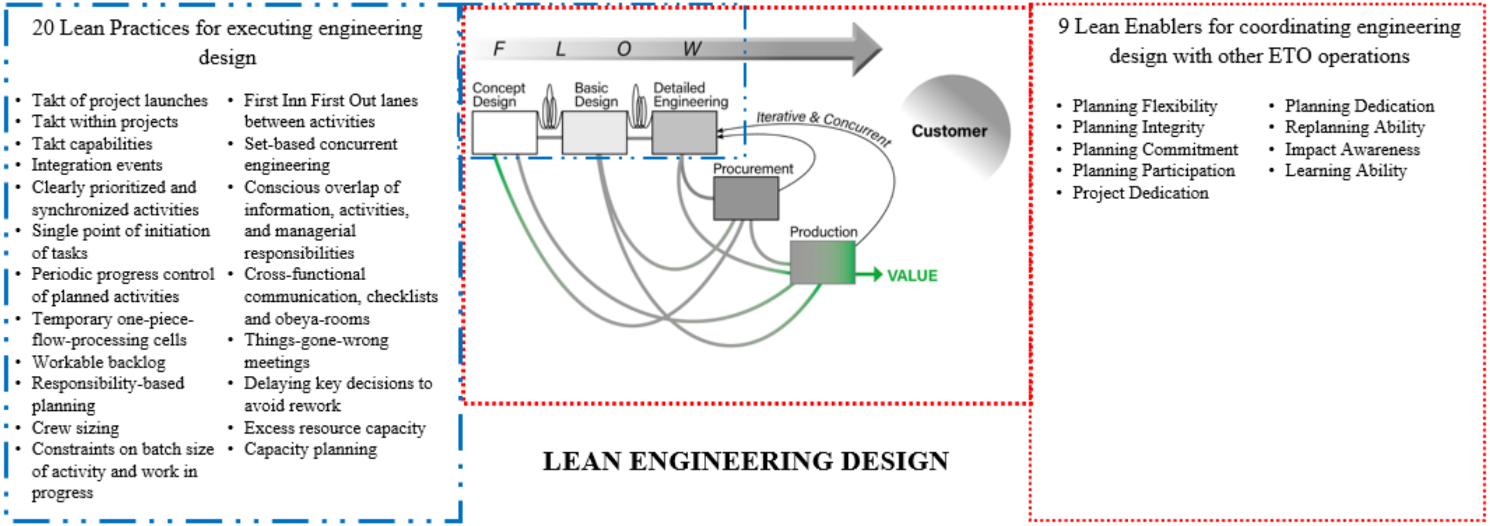
In line with the key findings, the concept of *lean engineering design* is proposed, which is discussed next.

5.3. Towards l*ean engineering design* in ETO operations

Lean engineering design is a novel concept that applies lean thinking adapted to the needs of engineering design, as found in ETO operations. Referring to the findings presented in Chapter 4 and highlighted in the previous sections, *lean engineering design* consists of two elements, as visualized in Figure 9.

The first element consists of 20 lean practices that when applied, improve the execution of engineering design. The second element consists of nine lean enablers that when applied, improve the coordination of engineering design with other interdependent operations, such as procurement and production. While the lean practices improve the execution of engineering design by leveling engineering workflow, the lean enablers improve the coordination of engineering design with other ETO operations by eliminating waste.

This dissertation aims to argue that it is of equal importance to apply lean thinking to both the execution of engineering design and the coordination of engineering design with other operations. The reason for this is that value in ETO operations is created through an operational value stream of sales, engineering design, procurement, and production, consisting of all the interconnected and mutually dependent activities that contribute to value creation (Rossi et al., 2017), as illustrated in Figure 3, Chapter 2. In other words, it is not enough to improve the execution of engineering design without improving its coordination with other ETO operations.



20 Lean Practices for executing engineering design

- Takt of project launches
- Takt within projects
- Takt capabilities
- Integration events
- Clearly prioritized and synchronized activities
- Single point of initiation of tasks
- Periodic progress control of planned activities
- Temporary one-piece-flow-processing cells
- Workable backlog
- Responsibility-based planning
- Crew sizing
- Constraints on batch size of activity and work in progress
- First Inn First Out lanes between activities
- Set-based concurrent engineering
- Conscious overlap of information, activities, and managerial responsibilities
- Cross-functional communication, checklists and obeya-rooms
- Things-gone-wrong meetings
- Delaying key decisions to avoid rework
- Excess resource capacity
- Capacity planning

LEAN ENGINEERING DESIGN

9 Lean Enablers for coordinating engineering design with other ETO operations

- Planning Flexibility
- Planning Integrity
- Planning Commitment
- Planning Participation
- Project Dedication
- Planning Dedication
- Replanning Ability
- Impact Awareness
- Learning Ability

Figure 9. Lean practices and enablers as a foundation for *lean engineering design*

Thus, how does *lean engineering design* address the typical characteristics of ETO operations, as outlined in Chapter 2? The four characteristics that this dissertation has focused on are high levels of uncertainty in product and process development, due to a high degree of customization; geographically dispersed engineering design and production; concurrent execution of operations to keep lead times short; and a high requirement of tacit knowledge to develop advanced and unique solutions. The following paragraphs discuss how lean engineering design contributes to addressing them:

First, due to high levels of uncertainty in product and process development during the early phases of engineering design, the product requirements are broadly defined in the beginning of the project and evolve iteratively as it proceeds (Hicks et al., 2001). These iterations involve customers, suppliers, and authorities. *Lean engineering design* aims to improve these iterations in order to remove obstacles concerning quality, resource utilization, lead time, and customer satisfaction, among others (Adler, 1995, Bertrand and Munstlag, 1993, Braiden et al., 1993, Little et al., 2000, Reddi and Moon, 2011, Terwiesch et al., 2002).

Second, due to ETO products' size and complexity, the company that manages the overall project often executes only a small part of the project that is performed by its own personnel and in its own production facilities. The greater part of the product's value is built with the help of suppliers and subcontractors (Dubois and Gadde, 2000). *Lean engineering design* aims to improve coordination among project partners, as well as improve the flow of engineering work to avoid production delays.

Third, to keep lead times short, ETO operations are often executed concurrently (Birkie and Trucco, 2016, Gosling et al., 2015). Consequently, design changes affect component production at all supplier tiers, making it difficult to align and control engineering activities and production. Similar to the statement in the previous paragraph, when ETO companies apply *lean engineering design*, potential quality issues that require rework can be avoided (Bogus et al., 2005, Hicks et al., 2000, Maier et al., 2008, Mello and Strandhagen, 2011, Terwiesch et al., 2002).

Fourth, ETO operations are driven by tacit knowledge as they deliver unique and highly customized solutions based on expert competence and experience (Emblemsvåg, 2017). When applied, *lean engineering design* puts individuals at the center of defining the scope and the content of each activity needed to deliver the ETO product (Hicks et al., 2000, Kjersem and Emblemsvåg, 2014, Mello, 2015), thus increasing the commitment level and the probability of meeting set deadlines (Ballard, 2014).

Finally, how does *lean engineering design* transform engineering design into a leaner approach? When applied to engineering design, the proposed concept of *lean engineering design* contributes to realizing several important lean aspects. First, the concept builds quality in the process (e.g., the process of planning and control as part of coordination), a main goal for the lean thinking concept and for Toyota (Ohno, 1988). Second*, lean engineering design* focuses on the flow of decisions (that create value), rather than purely resource utilization, by making the required information and knowledge available (Modig and Åhlstrøm, 2013). Third, decisions are made as late as possible without delaying the project, based on just-in-time information and knowledge, because more fact-based information becomes available as the project proceeds (Liker, 2019). Fourth, during planning, *lean engineering design* puts the frontline engineer first by letting the person who will execute the required task plan the activity in question. Therefore, this approach results in more realistic planned activities and a higher commitment to carry out the activities as planned (Ballard and Tommelein, 2011).

As such, elements of *lean engineering design* are regarded as facilitators of holistic information sharing and allow producing the right information in the right place at the right time. Sharing information holistically and efficiently among all participants reduces risk and is considered one of the main factors contributing to project success (Albert et al., 2017, Andersen et al., 2007, Hussein, 2013, Müller et al., 2012, Rolstadås et al., 2014, Yamin and Sim, 2016).

6. Conclusion

This chapter marks the end of this dissertation. It presents the key contributions of the knowledge gained through this research and heightens the study's main contributions for practice. This study's limitations are also presented, and opportunities for future research are identified.

Through a rigorous research process that has addressed relevant gaps in current theory, this PhD study makes several theoretical and managerial contributions. The common thread in this dissertation refers to describing and empirically demonstrating the applicability of lean thinking to engineering design, as found in ETO operations. This is an important contribution, as previous research has predominantly focused on industries producing either very large products, such as the aerospace industry (Oppenheim, 2011, Reinertsen, 2007), or a large amount of products, such as the automotive industry (Oliver et al., 2007, Ward and Sobek II, 2007), or on the construction industry (Ballard, 2000c).

In contrast, this dissertation suggests 20 lean practices and nine lean enablers that can be used to facilitate *lean engineering design* in ETO companies that deliver advanced individual solutions in very low volumes in the maritime industry. The potential benefits of the lean methodology might be indisputable, but the successful realization of such benefits is scarcely studied in empirically research (Liker and Morgan, 2011). As such, this dissertation offers an important empirical contribution by showing the potential impact of *lean engineering design* on eliminating waste and the potential linkages between lean practices and real work challenges related to unleveled engineering design workflow through extensive multiple in-depth case studies, which are scarce in the extant BOK (León and Farris, 2011, Letens et al., 2011, Liker and Morgan, 2011). Moreover, the contributions can be embedded in the debate on the role of non-physical business areas (such as engineering design) in ETO operations' value creation (e.g., Adrodegari et al. (2015)), as well as the discussion on the usefulness of lean thinking in project-based environments (e.g., Maylor et al. (2015)). The lean thinking methodology was born in practice and has been driven by practice since then (Jones and

Womack, 2016). In this dissertation, the proposed concept of *lean engineering design* is not defined solely from theory; rather, its elements are derived from close observations and interactions with real practice. As such, this research contributes to solving the accentuated problem of non-contextualization (Gosling et al., 2015) by showing how lean thinking is thoroughly adapted to the engineering design context. Table 12 summarizes the key contributions from the appended papers. The following sections highlight these key contributions.

Table 12. Summary of key contributions from the four appended papers

Key contribution / **Paper**	**#1**	**#2**	**#3**	**#4**
Key theoretical contributions				
Real-world challenges regarding poor execution of engineering design				**X**
20 lean practices to improve the execution of engineering design				**X**
Key engineering design wastes			**X**	
Nine lean enablers		**X**		
Concept of *lean engineering design*		**X**	**X**	
Key managerial contributions				
Analysis of how lean practices can be applied to improve the execution of engineering design by leveling workflow				**X**
Analysis of how lean enablers can be applied to improve the coordination of engineering design with other ETO operations by reducing waste			**X**	
Maturity model as a management tool that guides managers on their path to lean transformation	**X**	**X**		

6.1. Theoretical contributions

The first theoretical contribution of this dissertation refers to identifying and describing challenges that result in poor execution of engineering design. As previously described, the identified characteristics of ETO operations (e.g., high levels of uncertainty in product and process development) challenge an efficient execution of engineering design, which more often than not, leads to unleveled workflow and overburdened engineering resources, which in turn can lead to a decreased quality of engineering activities, longer lead times, and higher product development costs (Fiore, 2004, Morgan and Liker, 2006, Ward and Sobek II, 2007). In Paper 4, eight real-world challenges are identified, which sets the foundation for a more thorough investigation of which lean practices should be adapted to the ETO context in order to improve the execution of engineering design.

The second contribution proposes 20 lean practices that can overcome the identified challenges in Paper 4, and as such, improve the execution of engineering design. It differs from the earlier list of lean practices that refer mainly to production processes, with no specific focus on business processes, such as engineering design. In contrast, this research presents lean practices that specifically focus on improving the execution of engineering design by leveling engineers' workload to achieve a continuous workflow.

Third, by identifying key engineering design wastes (Paper 3), the research offers significant and original insights by establishing a generic list of defined wastes identified in ETO operations. Comparable to the eminent list of seven wastes in production, as defined by Ohno (1988) over three decades ago, this newer list of wastes in engineering design can equally inspire academics and practitioners to identify similar wastes in their projects or companies. This contribution is important as it can foster mobilization for systematic action, which is necessary when aiming at reducing the amount of waste (Oehmen and Rebentich, 2010).

Fourth, by presenting nine lean enablers (Paper 2), this research improves the coordination of engineering design with other ETO operations while eliminating waste. The nine lean enablers combine principles from LPS®, LPP, PDCA, TPDS, and Scrum, thus challenging traditional PM practices (Emblemsvåg, 2017, Nesensohn et al., 2014, Willner et al., 2016a). As such, when applying the nine lean enablers, the so-called waterfall principles of traditional PM are opposed, where project team members avoid pushing decisions on others but encourage engaging the frontline worker (e.g., lead engineer) to participate in the planning process and enabling him/her to make quicker decisions.

Finally, a key theoretical contribution is *lean engineering design,* a novel concept that applies lean thinking adapted to the needs of engineering design, as found in ETO operations. The concept consists of two equally important elements—20 lean practices and nine lean enablers. In so doing, this study provides updated insights on how *lean engineering design* addresses the typical characteristics of ETO operations. It assists in increasing the understanding of what parts of lean thinking are universal and what parts are context dependent.

6.2. Managerial contributions

With the overall aim of investigating how lean thinking can be adapted and applied to the execution of engineering design and its coordination with other ETO operations, the practical relevance of this work is indeed important. First and foremost, this dissertation provides empirical evidence that describes the applicability of the concept of *lean engineering design*. More precisely, evidence has been provided to demonstrate

- how lean practices can be applied to improve the execution of engineering design by leveling workflow and
- how lean enablers can be applied to improve the coordination of engineering design with other ETO operations by reducing waste.

In terms of practical relevance, the developed maturity model is regarded as a management tool that guides managers on their path to lean transformation. As most lean transformation journeys still fail (Netland, 2016) this research contributes to facilitating the implementation of lean thinking. To understand the transition from the traditional to the lean approach that allows better coordination of engineering design with other ETO operations, the proposed maturity model distinguishes among four levels of maturity. Following the concept of maturity, the development proceeds from a lower to a higher capability level. Once fully embedded in an organization, the presented maturity model can provide a safe management tool for constructive self-criticism and can be used to conduct self-assessments without the need for an external facilitator.

Finally, firms may find the proposed concept of *lean engineering design* useful in three main areas.

- First, applying *lean engineering design* will allow managers to transform their way of coordinating engineering design with other operations into a lean approach, and by doing so, they can realize their sought benefits of lean thinking. It is important to state that the proposed concept of *lean engineering design* is neither a tool nor a software program but a set of guidelines for how to transform traditional coordination in ETO operations into a lean approach.
- Second, following *lean engineering design* makes problems visible, supports finding solutions collaboratively, and teaches teams to identify breakdowns without imputing blame or guilt to any party; instead, it encourages learning from failures. In other words, the proposed concept allows practitioners to implement a system-wide lean approach rather than equipping managers with a single lean tool or technique.
- Third, by offering empirical evidence on how to apply *lean engineering design*, this dissertation contributes to improving engineers' skills and motivation in working in a lean environment, where project participants draw plans in coordination with one another and make decisions based on frequently updated information. Although *lean engineering design* does not minimize risk or uncertainty, it makes problems visible earlier, giving project teams more time to react. It fosters proactive elimination of constraints (prior to the stage when activities start running late) and therefore minimizes firefighting activities, which seem to be the norm in many of the studied ETO companies.

6.3. Limitations and suggestions for future research

This research has some limitations due to the nature of the sample used in this multiple case study. The case companies are located in Western Norway, and the insights obtained might thus be linked to contextual issues constrained by regional aspects. This point may be relevant because the data collected from 24 countries suggest that the implementation of lean principles highly depends on cultural aspects (Kull et al., 2014).

It is important to state that although the proposed maturity model applies lean principles, by no means does it measure the overall *leanness* of an ETO company. The lean thinking method is often referred to as a journey of individual and organizational learning, allowing more challenging and fulfilling work for those involved. On this improvement journey, it is crucial to acknowledge that an organization will never achieve its perfect state (Liker, 2017). This dissertation emphasizes that understanding the underlying enablers for lean engineering design is fundamental, though achieving the highest maturity level is not always the goal. The process should be tailored to each organization and each project's needs; therefore, future work on this matter is welcomed.

Similar to other lean research, it is difficult to point out one isolated key enabler or practice that improves overall performance (or a specific part of the performance). The belief that a lean thinking methodology works only if implemented as a system-wide approach, touching all parts of an organization, should be strengthened. Consequently, more research is needed to empirically evaluate the performance of ETO companies when utilizing *lean engineering design* or applying *lean practices* when executing engineering design.

Decisions allow progress in ETO companies. Information is needed for making decisions. This empirical investigation provides some reasons to believe that the quality or the *maturity* of the information shared within an iteration affects the quality of the iteration. In other words, project participants *either* make a decision based on the available information and push progress forward *or* continue/extend the iteration to gather more mature information before making a final decision. It seems to be a crucial managerial (and organizational) capability to standardize the process of judging maturity. It is certainly context specific; nonetheless, ETO companies would benefit from a holistic standardized procedure, which is thus recommended. Further research on this matter is welcomed as well.

Moreover, the research identifies an extensive list of wastes, as observed in ETO operations. Generating such a list is a critical starting point in creating awareness about major waste types occurring in engineering design, as well as mobilizing actions toward stemming, reducing, and eliminating waste (Oehmen and Rebentich, 2010). However, these interesting findings could further benefit from a comparative case analysis, which would allow linking waste occurrence to specific cases, thus providing a more comprehensive understanding.

Finally, during the years when this research has been carried out, the need for pursuing sustainable business approaches has become paramount. Introducing a circular economy has specifically been recommended for achieving sustainability (Geissdoerfer et al., 2020). While many companies still prioritize recycling in their business processes, it is, in fact, the least value-capturing loop in a circular economy. Sustainability is far better served by eliminating waste from the outset, when companies start designing their products (Tse et al., 2016). Consequently, it seems promising to apply *lean engineering design* as a facilitator of sustainability/a circular economy; therefore, future work on this matter is welcomed.

6.4. Final remarks

A PhD dissertation presents factual accounts, and this dissertation does not suggest that any of the case studies or Toyota (which is credited for the invention of lean thinking) has a perfect way of executing engineering design or coordinating engineering design with other operations or has perfect engineers. ETO companies develop unique, complex, and advanced solutions that will always be far from perfect. What this dissertation stands for is the concept of *lean engineering design* that represents an ideal that ETO companies can strive for. The philosophy of lean thinking is to allow problems to surface, solve them one by one, and then learn so that the same problems do not recur. Thus, to apply lean thinking to ETO operations and harness its full potential for improvement, no solutions to problems should be provided. Instead, the lean thinking approach should provide a guiding path for organizations on how to succeed with problem solving. In other words, all employees need to be trained in identifying the problems that hide in ongoing processes and be taught how to solve them. Hopefully, this dissertation has provided tools, frameworks, generic waste lists for inspiration, as well as practices that can be applied to assist in succeeding with recognizing and solving problems in ETO operations.

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Appendix A: Interview guide

General information Informant: (Name, position, in the position since when) Company/division: (name, main products, number of employees, annual revenue)

Planning and control environment:

1. Could you describe in general terms the engineering and manufacturing planning processes? How do you come up with the project's lead-time? How do you elaborate your budget of the project in terms of hours and costs?
2. What are the challenge of the planning and control processes?
3. In which stages of your process from order request to delivery, significant variability in the flow of information and materials occur? Why does this variability happens?
4. What are the requirements to release a task to suppliers and workers? How is the interaction and involvement with the project participants (both own personnel and sub suppliers) when it comes to planning a project?
5. When do the milestone in the master plan (if they have) turn into detailed work packages?
6. How often do you update your planning? Are there any meetings where commitments are established? Do people come prepared to meetings?
7. How do you control the processes (design and production)? How do you evaluate and measure progress?
8. In rough terms, what would you say is the percentage of failure of projects in terms of time, budget or quality due to poor planning and control? Are the reasons for non-completion of task investigated further to prevent it from happening again?
9. What would you say is more costly: To deliver days/weeks later than planned or increase resources and other elements to finish on time? How is manning performed?
10. Have you experienced that greater progress is reported than what is the case? If so, what was the consequences and why do you usually notice it?
11. Do projects vary a lot in terms of participating stakeholders? (e.g. suppliers) What type of relation do you have with your different suppliers?

Appendix B: Identifying and rating waste in engineering design

Step 1: Discuss in group if any of the 8 types of wastes exist in your ETO projects. Give examples how these wastes expresses themselves during your engineering design process.
Step 2: Rate the three most present wastes from 1 – 3 (1 being present and 3 least present)

Waste	**Group 1 (illustrative example)**
Transportation	Waste (Who is doing what, assigning based on the competence level) If you have assigned to wrong people Sending drawings to wrong persons Physical handling of drawings (final distribution of the drawings)
Inventory	External approval of the reports to ensure if this is the right direction are not
Movement	Manning of the projects, people moving from one project to another Too much to do, multitasking Difficult to be efficient
Waiting (3)	For information from external (DNV, Customer, third party) and internal stakeholders (different departments, get them in sync) Waiting for the successors Information: Technical input, technical decision For acceptance from internal and external stakeholders
Overproduction (2)	Companies don't have much to do now, engineers start to do the drawing early which might cause re-work Bringing experiences from previous project to new. You might end up producing documents, procedures more than what was required. Previous methods may cause over production Solution: Debriefing to help clients/engineers
Over-processing (1)	They forget what the purpose of the product is and where the installation is going to happen. Overproduction and over-processing are very dangerous for the business now as people are doing much more than what is required to save possible jobs. There are too many aspects of over-processing and overproduction
Defects	This is mainly due to stop and go aspects, movement, Due to lack of competence Due to copying previous design
Unused employee creativity	Involving the engineer in the front loading The focus is too much on fulfilling the wrong requirements than on the value added Choosing the right engineer for the correct job, right competence for the right project You will always have a handful who are very good and very creative

Appendix C: Presence of Supporting Conditions

(Selection of quotes and phrases)

Enabler	**Definition**	**Waste present in ETO**	**Implication to engineering design. How and why can enablers address the waste?**
Planning flexibility	Flexibility within the planning process through updating and replanning as often as needed.	Waiting Over-production Over-processing Defects **Movement -** ***Sharing same resources on multiple projects leading to stop and go and many handovers*** Inventory Transportation Unused employee creativity	Creating and updating planned activities, as well as replanning delayed activities on an ongoing basis keeps the plan alive and realistic. As an example, delayed activities are not just stacked on top of already planned activities for the next period.
Planning integration	Integration of all plans from the different departments	Waiting **Over-production -** ***Starting activities prior to planned date, which leads to wrong output.*** Over-processing Movement Inventory Transportation Unused employee creativity	Integrating all activities (within the ETO company's different departments, as well as external contributors) allows a clear overview of the current situation avoids silo thinking and supports alignment.
Planning commitment	Commitment to realistic and relevant activities through involvement	**Waiting -** ***Waiting for calculations as the activity was stopped, as other projects were more important.*** Over-production Over-processing Defects Movement Inventory Transportation Unused employee creativity	Collaborative planning generates better communication and deeper commitment. Resulting in a more realistic workload for engineers, reducing firefighting and delays.

Planning participation	Holding well-structured planning meetings whenever new information is available and decisions need to be taken.	Waiting **Over-production -** ***Over-specifying functionality of the product.*** Over-processing Defects Movement Inventory Transportation Unused employee creativity	Making better decisions more efficiently by involving all participating departments in planning meetings. Everybody is represented and prepare; nobody leaves until agreement and commitment is achieved.
Project dedication	Applying tools to measure and visualize the overall performance	**Waiting -** ***Waiting for input or decisions.*** Over-production Over-processing Defects Movement Inventory Transportation Unused employee creativity	Earned vale management (EVM), measures the project's evolution in relation to the planned budget, time, and resources, enabling the management team to take the necessary actions and keep the project on the most favorable path.
Planning dedication	Applying tools to measure and visualize progress of planned activities.	Waiting Over-production **Over-processing -** ***Being too creative; drawings containing too many details.*** Defects Movement Inventory Transportation Unused employee creativity	Percent plan complete (PPC) measures the percentage of activities completed as planned. The PPC is used as a mode to obtain involvement and commitment from the all participants.
Replanning ability	Ability to re-plan new or delayed activities	Waiting Over-production Over-processing **Defects** ***Making wrong assumption due to incomplete customer specifications.*** Movement	When new activities occur (e.g. due to changes or defects) planned activities need to be replanned, including considering the consequences of such changes/delays on other activities from other disciplines. Planning needs to be connected to check and act, meaning that only if the

		Inventory Transportation Unused employee creativity	team checks status of planned activities, and acts accordingly (replan if necessary) realistic progress can be achieved.
Impact awareness	Ability to estimate impact of decisions	Waiting Over-production Over-processing **Defects** Movement Inventory Transportation Unused employee creativity ***Defects in form of wrong drawings due to misunderstanding or lack of coordination.***	When decisions are taken (due to changes or defects) it is essential to consider the impact on activities. It is essential to consider the bigger picture rather than optimizing individual departments.
Learning ability	Ability to disseminate experiences and lessons learned	Waiting **Over-production** Over-processing Defects Movement Inventory Transportation Unused employee creativity ***Making calculations and analysis that are unnecessary because of project similarities.***	Problems, root causes and anticipated solutions need to be made shared among all ETO project participants to allow reflection, learning and improvement for the future.

Part II

Appended Papers

Paper I

FROM FIRST TO LAST PLANNER

APPLYING A CAPABILITY MODEL TO MEASURE THE MATURITY OF THE PLANNING PROCESS IN ETO

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Abstract.

Engineered-to-order (ETO) networks are dynamic and hard to define, and their planning and control functionalities are commonly affected by the actions of suppliers and customers. Frequently, projects experience delays, budget overruns, and quality defects. Consequently, there is a need for project management that synchronizes engineering and production processes throughout the network.

The aim of this study is to develop a project planning maturity model (MMPP) in order to improve project performance in ETO manufacturing networks. Moreover, a multiple case study approach is used to test the applicability of the developed maturity model. The results of the case studies from three ETO case companies show that there is (1) no or low degree of standardization of the planning processes, and (2) there is little or no integration between engineering and production planning processes.

Keywords maturity model, project planning, project management, Engineered-to-order (ETO), Lean

1 Introduction

Planning is the process of thinking about and organizing the activities required to achieve a desired goal by creating and maintaining a plan. In managing and controlling projects, planning is an important factor that can contribute to both success and failure of meeting the projects objectives. As early as 1988, Pinto and Slevin [1] listed a number of factors that contribute to project success during the execution phase, such as *defined project goal, effective communication, commitment from senior management and project planning and monitoring*. In 2002, Cook-Davies [2] complemented this list

adfa, p. 1, 2011.

by adding *scheme for performance measurement and report* (e.g. Earned value) as a success factor to project success. Measuring how well the process of planning is performed can be a difficult task due to its complexity and interdependence with other processes.

The term project maturity is used as measurement of an organization's ability to execute projects. [3]. As shown by Project Management Institute (PMI) many maturity models exist (PMI, 2015). Many of these models are rather limited in scope and focus on the categorization of the actual behavior of the organization. Our research objective is to create a deeper understanding of the maturity of the project planning process by presenting a maturity model that can map the maturity of the project planning process within ETO networks. ETO networks are dynamic and hard to define, and their planning and control functionalities are frequently affected by the actions of suppliers and customers which typically may result in excessive inventories, long lead times low customer satisfaction and poor resource allocation [4]. Many projects experience delays, budget overruns, and quality defects [5]. Design changes are inevitable and make it difficult to coordinate projects with multiple subjects and actors [6, 7]. Excellent and successful ETO projects require rapid reaction capability for adaptation [8]. Consequently, there is a need for project management that synchronizes engineering and production planning in the value chain. Despite the significant challenges associated with this, little research has been done in this area [4], and more specifically little has been done related to integration of project management (activity-based) and production planning and control (material based) as a way of responding effectively to design changes.

ETO products are highly customized and contain a variety of components. Main products have complex structures where some components are highly customized (as a management system and advanced technological equipment), while others are standardized (as some steel components) [9]. This high complexity means that companies need to coordinate the engineering, procurement, manufacturing, assembly and installation in supply chains efficiently. Ordinary ERP systems are not well suited to handle the myriad of product specifications and parameters in an ETO supply chain and support to manage design changes are extremely limited [10]. There is a great need for planning methods that can assist the chaotic production in complex ETO environment [8].

This paper therefore aims at highlighting the challenges of an ETO project based production, and argues that an integrated and well-structured planning process can enhance project and ultimately overall business performance. This is done by applying known theories within lean construction and project management as well as performance measurement literature.

2 Theoretical discussion

2.1 Project Management and Earned value management

In managing and controlling projects, planning is an important factor that can contribute to both success and failure of meeting the projects objectives. As early as in 1988, Pinto and Slevin [1] listed a number of factors that contribute to project success during the execution phase, such as *defined project goal, effective communication, commitment from senior management and project planning and monitoring*. In 2002 Cook-Davies [2] complemented this list by adding *scheme for performance measurement and report* (e.g. Earned value) as a success factor to project success. Measuring how well the process of planning is performed can be a difficult task due to its complexity and interdependence with other processes.

Earned value management (EVM) is a technique to measure project progress by comparing the baseline of the project with reported physical results, the resources consumed and the remaining hours to the completion per activity [11]. A good performance metrics used by EVM is the Cost Performance Index (CPI). CPI calculates and predicts costs at completion of the project within a finite range of values after only 15-20 per cent completion of the project [12].

2.2 Lean construction, Last Planner System and Lean Project Planning

Lean construction applies production-based ideas from lean thinking to project delivery within construction industry [13]. In such projects, lean changes the way projects are managed during the building process. Lean Construction is based on lean production philosophies that thrive to maximize value and minimize waste expressed in specific project management techniques [14]. Ever since the 90s, lean construction community has recognized the need for a change in the way traditional project management plan and measure activities in a project. One of the best examples is the invention of Last Planner System (LPS) by Ballard [15] [16]. The role of LPS is to increase planning reliability by decreasing workflow variability, through recognizing and removing activity constraints, identifying root causes for non-completion of plans and monitoring its improvements by means of Percentage Plan Complete (PPC).

Kalsaas [17] and Emblemsvåg (2014a) point out that LPS is not able to handle advanced engineering design work and needs a better instrument to measure physical progress for such activities. By introducing Lean Project Planning (LPP) Emblembsvåg attempts to combine elements of LPS and EVM [18]. LPP is based on Lean thinking and applies the Plan Do Check Act (PDCA) cycle, a basic problem-solving approach, which in LPP context involves making problems visible, finding proper solutions, checking the result and acting on deviations [18].

2.3 Maturity models

The planning process as well as organization as such, evolve over time and have to pass several stages of development or maturity. Ever since the late 70s, different types of models have been used to map and measure this path of development.

Nowadays, maturity models are widely used and a systematic mapping study undertaken by Wendler [19] showed that alone in 2009 and 2010, 62 academic articles on maturity models were published. The focus of these publications is still software engineering and as up-today there are few maturity models on planning.

A maturity model consists of a sequence of maturity levels for a class of objects. It represents an anticipated, desired or typical evolution path of these objects shaped as discrete stages. This definition by Becker et al. [20] severs as a starting point for the conceptual design of our maturity model on project planning where we combine elements of LPS and LPP to design a project planning process that will reduce the challenges observed within ETO manufacturing organizations in regards to planning.

3 Method

This study is based on a case study and as there is little previous research in this field, this topic calls for qualitative research approach [21]

The choice of method is closely related to the type of research question [22]. The purpose of this study is to explore and describe the applicability of performance measurement tools (maturity model) in order to map the engineering and production planning processes in ETO networks. The elements of the maturity model are drawn from theories of project management, lean planning as well as performance measurement literature and selected in cooperation with planning and project management personnel from the case industry. Studies undertaken by Bitici et al. [23] showed that maturity models with certain characteristics, promote organizational learning as well as enabling efficient and effective assessment of the performance management practice of the organization.

The empirical basis for this study has been based on three case studies representing three ETO manufacturing companies in the maritime industry in Norway. These aforementioned companies deliver highly complex and special heavy lifting as well as pressure tank equipment for the offshore industry. The main business activities of the said case companies are designing, manufacturing and testing and commissioning and engages 500 hours of engineering, 500 hours dedicated to procurement, fabrication and production, as well as up to 2000 hours of assembly and testing. Lead times can vary from nine to 12 months. Each solution is highly customized and designed to meet individual customer requirements.

This Norwegian industry experiences increased global competition and cost pressure. Many Norwegian manufacturing companies are therefore moving some or all of their operations to low-cost countries. Changes in customer requirements are frequent throughout the entire project execution phase which requires detailed and real time planning with proper change order management systems in place. Effective planning and control is a key to success for companies in such project, low volume environment.

The main data collection was undertaken through semi-structured, focused interviews and observations as well as discussion and site visits over a one and a half year period in close cooperation with key personnel.

4 Results

The following part presents the findings of our study. After studying our case industry the following common characteristics were identified:

- ETO manufacturing environment
- Project based production
- Expressed need for improved planning process (few resources dedicated to planning, little competence)
- Plans are too difficult to update. They were drawn at an early stage but not updated and lose therefore validity and value. Planning was done at the high level without including the person that are executing the activities.
- Outsourced production which leads to phased based project management
- Many changes from customers lead to a need of flexible and dynamic planning.

In order to structure and improve the process of planning a maturity model for project planning (MMPP) was designed including six processes/ parameters (Table 1).

Table 1. Maturity model for project planning (MMPP)

1. **Level of flexibility** -This parameter defines how flexible the plan is, expressed in how often and at what level the activities within the project plan are updated.
2. **Level of integration** -This parameter defines how integrated the plans are - are all disciplines (e.g. design and engineering, steel work, piping, assembly) integrated in one common plan?
3. **Level of autonomous planning -** This parameter defines the way the plan is made – Is it a typical top-down approach or do all disciplines engage and commit to one common plan?
4. **Project plan meetings -** This process defines the existence and regularity of dedicated project plan meetings. Do all disciplines have to attend?
5. **Project performance measurement (EVM)** -The fifth parameter defines how project performance is measured? Ultimately we are looking for Earned Value management reports from all disciplines.
6. **Physical progress measurement (PPC) -** Finally the last parameter defines the level of usage of physical progress measurement (PPC).

As the planning process is enhanced by lean project planning approaches it evolves over time, starting with poor planning at the first planner level moving to second and third and finally evolving to the final – *the last planner* – level of maturity.

Table 2. Maturity model for project planning (MMPP)

Parameters/ Process	First planner/ Ad hoc	Second Planner/Standardized.	Third Planner/ Defined	Last Planner/ Optimized
Level of flexibility	The plan is created at the beginning of the project. No updates at later stages.	Random updates of high level activities only.	Pre-set updating dates at all level of activities.	Updates as often as required – all level of activities.

Level of integration	No common plan for all project disciplines. Some disciplines have their own plan	Some project disciplines are taking other proj. disciplines into consideration when making the plans.	Some project disciplines are taking other proj. disciplines into consideration when making the plans. No common plan exists.	One integrated plan for all project disciplines.
Making the plan	The plan is created at the high management level	Each discipline makes own plans.	Some project disciplines are involved in creating a common plan. No commitment from participants.	All project disciplines participate and commit to one common project plan.
Project planning meetings	Random plan meetings no formal agenda.	Regular plan meetings with no formal agenda nor obligatory participation	Regular plan meetings with formal agenda, obligatory participation with no formal reporting	Regular plan meetings with formal agenda, obligatory participation for all project disciplines with formal reporting
Project performance measurement (EVM)	No or random reporting	Reporting at project top management level.	Reporting from some project disciplines on a standardized report.	All project disciplines report on a standardized report. (Integrated EVM)
Physical progress measurement (PPC)	No physical progress reporting.	Physical progress reporting at project management level	Physical progress reporting from some project disciplines on a standardized report.	Physical progress reporting from all project disciplines on a standardized report. (Integrated PPC)

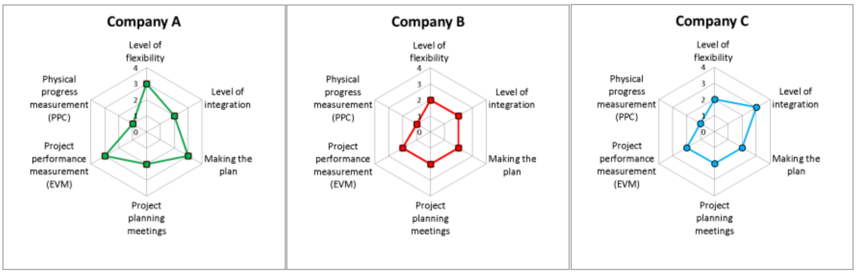

Fig. 1. First AS-IS measurement of the planning process

5 Conclusion

In order to structure and improve the process of planning a maturity model for project planning (MMPP) was designed. The elements of the maturity model are drawn from elements of LPS and LPP and selected in cooperation with planning and project management personnel from the case industry resulting in six parameters for evaluation. A first As-Is measurement of the planning process within three ETO companies operating in the Norwegian offshore supply industry was presented. We see especially low maturity in regards to the integration of all project disciplines and physical progress measurement. Meetings and information exchange (updating the plan) are not standardized. This confirms the hypothesis of an ETO industry that is characterized by informal planning and information exchange. Maturity in any organizational process evolves over time. In alignment with performance measurement literature we believe that by mapping and visualizing the steps to maturity organizations can succeed more easily with implementing a well-functioning and standardized planning process.

6 Future research

Wendler [19] points out that most of the contributions within MMs look at the design process of models or the applicability of existing models to other areas but that too few contributions within MMs focus on validation and implementation of models. The conceptual maturity model presented in this paper will be further developed and validated and maintained in collaboration with the Norwegian offshore supplier industry.

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Paper II

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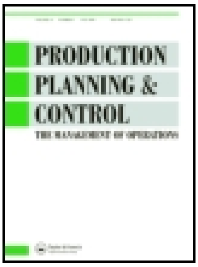
Paper III



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Understanding and eliminating waste in Engineer-To-Order (ETO) projects: a multiple case study

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ABSTRACT
This article explores how waste reduction approaches as found in lean thinking can be applied to engineering design in Engineer-To-Order (ETO) projects based on a multiple case study of ten companies over a 2-year period. ETO projects deliver capital goods that are customised to individual customer requirements. Customisation and ultimately value generation are achieved through an iterative engineering design process. Although inevitable, iterative engineering design allows much leeway for waste generation, expressed in higher costs and longer lead times. Accordingly, this paper investigates the iterative nature of engineering design in current practice and discusses how these iterations create wastes. It applies the concept of lean engineering design and elaborates on how this concept can eliminate wastes. The findings extend the literature on lean thinking by demonstrating its applicability to engineering design and provide a unique description of the most common wastes found in ETO projects. Furthermore, this article provides managerial implications on how lean engineering design can eliminate wastes and ultimately improve ETO project performance based on lessons learned from the case companies.

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KEYWORDS
Lean; engineering design; Engineer-To-Order; product development; waste

1. Introduction

Companies following an Engineer-To-Order (ETO) strategy design, engineer, produce and deliver products to meet customers' unique requirements. ETO products are typically high-value capital goods; due to their uniqueness and complexity, they are delivered as projects involving several specialised disciplines (Gosling and Naim 2009; Hicks, McGovern, and Earl 2001; Little et al. 2000; Willner et al. 2016).

ETO products achieve a high degree of customisation through an iterative engineering design process described as comprising several repeated phases that enclose a feedback loop after a set of phases has been completed (Fernandez and Fernandez 2009). Consequently, a product's requirements are broadly defined in the beginning of a project and evolve iteratively as the project proceeds. During this process, preliminary drawings are produced to improve the design and provide alternative solutions, when approved by the contracting parties and the regulatory bodies and then released for production (Ulrich and Eppinger 1999). Information is passed back and forth several times before final approval, resulting in numerous engineering design hours that constitute a significant amount of the total hours used for project delivery (Willner et al. 2016). Additionally, the amount and duration of iterations are difficult to predict, posing challenges concerning quality, resource utilisation, lead-time and customer satisfaction (Little et al. 2000; Reddi and Moon 2011; Terwiesch, Loch, and De Meyer 2002).

Empirical studies reveal that organisations spend over 50% of engineering design activities on non-value-adding activities, while the remaining 50% is split between value-adding and non-value-adding-but-necessary activities, (see e.g. Ballard 2000; Bonnier, Kalsaas, and Ose 2015; Freire and Alarcon 2000). More research is needed to fully understand the nature of iterative engineering design and how its execution can be managed efficiently to minimise waste.

To improve engineering design, organisations find guidance in lean thinking (Nepal, Yadav, and Solanki 2011) where the reduction in excessive process variability, the creation of pull-based flow driven by customer requirements, and waste elimination are perceived as key elements (Morgan and Liker 2006; Reinertsen 1997; Sugimori et al. 1977; Walton 1999). Waste elimination is the focus of this study. A method to structure improvement activities in the engineering design domain comprises the nine lean enablers developed by (Jünge et al. 2019). It proposes lean improvement approaches within planning, control and follow-up of engineering design processes.

Thus, the research aims to develop a deeper understanding and a theoretical basis for the application of lean in

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engineering approaches in the ETO context. Accordingly, the research purpose is to address the practical problem of extensive waste as found in engineering design through a lean approach without jeopardising value creation. First, the paper explores the iterative nature of engineering design in current practice in ETO projects and describes how these iterations generate both value and wastes. Second, the underlying nature of waste in the engineering design context is characterised and then mapped in ETO projects. Third, the paper applies the nine enablers of lean engineering design (Jünge et al. 2019) and demonstrates how they can address the main wastes in engineering design.

As such, this article contributes to the growing body of research discussing lean thinking and its applicability to different business areas (Birkie and Trucco 2016; Black 2007; Hoss and Schwengber ten Caten 2013; Jasti and Kodali 2015; Johansson and Osterman 2017; Towill 2007; Viana et al. 2014; Yadav et al. 2019) in general and refines the concept of lean engineering design (Jünge et al. 2019) by an extensive aggregated case study (Childe 2011) in particular.

2. Current practice and pertinent literature

This section presents the current practice of engineering design in ETO projects, specifically the way that its iterative nature leads to waste. It introduces lean thinking that focuses on the concepts of value and waste, illustrating how value is created in ETO projects. The section concludes by presenting the lean concept in engineering design for ETO projects (Jünge et al. 2019). Lean engineering design combines nine lean enablers and is the reference for this study's investigation on how such an approach can eliminate waste.

2.1. Engineering design in ETO projects

For companies following an ETO strategy, engineering design is the process of evolutionary or incremental change through which a series of relatively minor modifications to a product add up to substantial changes in the product's appearance, functionality, cost and quality of the product over time (Alderman, Thwaites, and Maffin 2001). Such changes are less likely to emerge from the research and development department but are part of the day-to-day processes of applying scientific and engineering knowledge to technical problems and optimising potential solutions within the requirements and constraints set by material, technological, legal, environmental and human-related considerations (Pahl et al. 2007). In ETO projects, engineering design is conducted through three phases: concept phase, basic design, and detailed engineering. During the concept phase, the main concept is designed; this period ranges from days up to several years, depending on the market situation and the design's complexity. At some point, the contract is awarded, a project organisation is formed, and the basic design phase starts. Typically, a project manager leads the project organisation, comprising representatives of all relevant disciplines, such as engineering, procurement, and construction (EPC). A project planner normally assists the project organisation. To keep lead times short, EPC follows a near-concurrent fashion (Emblemsvåg 2014a). The idea of concurrence suggests the simultaneous involvement of all relevant disciplines throughout the project.

Detailed engineering follows, including the production of all drawings required for production. ETO projects require flexibility to understand and adjust to changing customer requirements as well as the ability to translate these requirements into solutions. An important notion here is that customers are willing to pay extra for this flexibility compared with typical manufacturing, where the product is defined in detail before production, and changes outside the initial design become impossible. In other words, the master data required to define the ETO product are not – or even cannot be – fully developed when the contract is signed (Emblemsvåg 2020) but need to be developed iteratively, generating both value and waste.

2.2. Applying lean thinking to engineering design

ETO companies critically depend on engineering design (Anderson 2008); therefore, improving its overall management can yield significant operational benefits (Reinertsen 2005). However, organisations that succeed in developing and engineering products efficiently and effectively, year after year, are rare (Ballard 2017; Rossi, Morgan, and Shook 2017). A notable example of consistent success is Toyota Motor Company. Toyota's way of developing and manufacturing cars was first introduced to the public as lean manufacturing or lean thinking. Lean thinking is a holistic management philosophy that allows problems to surface and then used the process of solving them by encouraging learning cycles on how to reduce the risk of repetition (Liker and Morgan 2011) as defined by five key principles (Womack and Jones 1996).

A lean organisation's core purpose is to deliver value to its customers, with value defined as everything that the customer is willing to pay for (Womack and Jones 1996). In ETO projects, value assumes a specific meaning and its creation starts with identifying what customers really want, followed by understanding and articulating customer-defined quality. Value is then created through an iterative, concurrent operational value stream consisting of all the interconnected activities that contribute to value creation (Rossi, Morgan, and Shook 2017). Figure 1 illustrates a typical iteration process that moves from the originator (e.g. the customer) to the engineering department (which, e.g. estimates impacts on procurement and production) to a third-party agent (e.g. for independent verification), back to the engineering department and finally returning to the customer. On this iteration path, engineering design generates either value, as the degree of product specification becomes clearer, or waste in the form of unnecessary costs and increased lead time. A decreased risk is also regarded as a means to increase value as this will improve the likelihood of delivering the required product specification within the required schedule (Emblemsvag 2017).

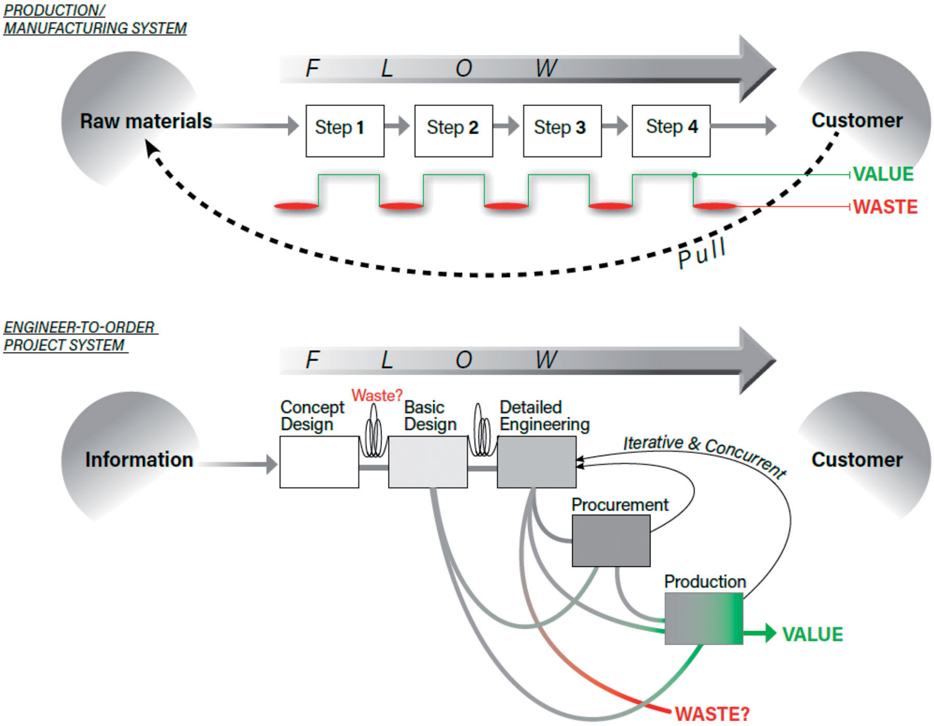


Figure 1. The value creation model as applied to Engineer-To-Order projects.

Waste in engineering design, as in any other process, is a symptom of not operating at a high efficiency or effectiveness level. Extant literature provides various definitions of waste because it disguises itself in different ways, according to the context in which it appears (e.g. Formoso, Isatto, and Hirota 1999; Koskela 2004; Macomber and Howell 2004; Mascitelli 2007; Poppendieck 2017; Stevenson, Hendry, and Kingsman 2005; Thürer, Tomašević, and Stevenson 2017; Womack and Jones 1996). To understand waste, it is grouped into different categories; this article follows the classic categories of waste from manufacturing, as famously introduced by Ohno (1988). With some adjustments, these are applicable to engineering tasks (Rossi, Morgan, and Shook 2017).

1. Overproduction – Producing more, faster, or at an earlier stage than is required by the next process (or customer).
2. Over-processing – Performing unnecessary processing on a task.
3. Waiting – Waiting for work to be completed by a previous process or person.
4. Defects – Any kind of correction, such as late engineering changes.
5. Movement – Excess movement or activity during task execution
6. Inventory – Build-up of more material or information than required
7. Transportation – The movement of documents/information/project tasks from person to person
8. Unused employee capabilities – Failing to develop and/or utilise human capabilities

2.3. Definition and characteristics of lean engineering design

Existing lean approaches targeting waste reduction, as found in the literature provide valuable insights applicable to ETO. However, there are several major differences in the systems to which these approaches are applied, for example, new product development (Hoppmann et al. 2011; Mascitelli 2007; Morgan and Liker 2006; Oppenheim 2011; Reinertsen 1997; Ward and Sobek 2007), construction (Ballard 2000; Emblemsvåg 2014b, Tommelein 1998) and engineering design it the ETO context. First, a typical ETO product is produced only once (or in very low numbers). As such, the engineering design process hardly involves finding the optimal production process (i.e. the engineering design effort cannot be capitalised through many sold items afterwards). Second, in cases where the ETO company owns the production facilities, the supplier of production is given. Third, the project profitability needs to be evaluated upfront. Once the contract is signed, the project cannot be stopped. On the contrary, fines or penalties are imposed for incomplete or late fulfilment (Emblemsvåg 2020). Fourth, although ETO production follows a customisation methodology, it has a higher potential for reusing manufacturing systems (e.g. shipbuilding compared with construction projects). Fifth, ETO normally delivers a product to an external customer that waits while product development projects follow a company-internal schedule. This puts the entire ETO project under much pressure and the need to plan and control the project becomes paramount in ETO (Alderman, Thwaites, and Maffin 2001). Additionally, customers typically impose strict reporting and control regimes in an effort to manage their risks. To overcome the specific challenges encountered in engineering design in the ETO context, Jünge et al. (2019) proposed the concept of lean engineering design, combining nine lean enablers. As mentioned in the introduction, this paper uses this set of nine enablers as a reference for lean thinking applied to engineering design and defines the authors' investigation on how such an approach can address waste in ETO project contexts. The underlying rationale is that the proposed nine enablers combine the lean thinking principles, as applied to construction, shipbuilding and product development (Ballard 2008; Emblemsvåg 2014b, Liker and Morgan 2011), agile software development (Schwaber, Sutherland, and Beedle 2013) and the scientific problem-solving plan-do-check-act cycle (Deming 1986). First, the enablers build quality in the process (of planning and control), a main goal of the lean concept. Second, lean engineering focuses on the flow of decisions (that create value), rather than purely resource utilisation, by making the required information and knowledge available (c.f. Modig and Åhlstrøm 2013). Third, decisions are made as late as possible without delaying the project, based on just-in-time information and knowledge, because more fact-based information becomes available as the project proceeds. Fourth, lean engineering puts the frontline engineer first by letting the person who will execute the required task plan the activity in question. This approach results in more realistic planned activities and a higher commitment to carry out the task as planned (c.f. (Ballard and Tommelein 2012).

As such, the nine enablers are regarded as facilitators of holistic information sharing and allow producing the right information in the right place at the right time. Sharing information holistically and efficiently among all participants reduces risk and is considered as one of the main factors contributing to project success (Albert, Balve, and Spang 2017; Andersen, Henriksen, and Aarseth 2007; Hussein 2013; Müller, Geraldi, and Turner 2012; Rolstadås et al. 2014; Yamin and Sim 2016). Moreover, these enablers were developed in close collaboration with ETO practitioners, following a design science methodology (Jünge et al. 2019). More specifically, theoretical discussion on lean was combined into a design science artefact and later validated and refined in practice. Therefore, the nine lean enablers have not been derived from not only theory but also from observations of and interactions with real practice within ten companies over a 2-year period, an important aspect when testing and informing existing theory (Jones and Womak 2017). Table 1 provides a more thorough introduction to the nine enablers.

3. Research methodology

The purpose of this research is to address the practical problem of how the iterative nature of engineering design creates waste and how to minimise such waste through a lean approach. During the engineering design process, the ETO project organisation gathers, discusses, evaluates, and eventually transforms information into value. The assumption that a holistic, iterative and collaborative engineering design approach lies at the heart of value creation in ETO projects, builds the foundation for the data collection and analysis in this research (Kerzner 2013; Oehmen and Rebentich 2010).

This research applies a case study approach as it provides an explanation for contemporary social phenomena in their natural settings and cultural contexts, and is especially suitable for investigating phenomena in highly complex contexts, such as ETO projects (Stuart et al. 2002; Yin 2014). The case approach generates new insights, which are difficult to gain through purely analytical or statistical analysis (Meredith 2001; Yin 2014).

More specifically, this paper applies a Scandinavian research approach, allowing the researchers to engage in deep collaboration with the selected case companies. According to Karlsson (2009), this approach is suitable when aiming to develop academic and company-level knowledge simultaneously. Ballard (2000) highlights the need for empirical studies to understand whether iterations generate waste or value. Other scholars (e.g. Black 2007; Hoss and Schwengber ten Caten 2013; Jasti and Kodali 2015; Johansson and Osterman 2017; Towill 2007) call for more case studies of non-automotive industries to assist in validating the applicability of lean principles. Thus, a case study approach provides a unique opportunity to understand the engineering design practices of the case organisations in their entirety without necessarily isolating them from their contexts (Hartley 1994).

3.2. Case selection

When conducting case studies, the selection criteria are of crucial importance, because the knowledge derived from the selected cases should provide valid information to support the explanations when aiming to build or further develop theory (Eisenhardt 1989). The initiative behind this research was triggered by several research workshops in collaboration with companies that were preoccupied with decreasing lead-time and the costs of project-based work. The case companies selected deliver ETO-products, such as offshore-specialised vessels, cranes, technologically advanced pressurised vessels, propellers, thrusters and casting equipment. Based on this, the following inclusion criteria were developed: The companies should (1) deliver mainly ETO products, (2) have ongoing projects that implement lean concepts and (3) be willing to provide the involved researchers with relevant access to project data and procedures to ease the mapping of targeted engineering design processes (Table 2).

3.1. Data collection and analysis

The data for the empirical enquiry were obtained over a 2-year period following four phases (Figure 2). Table 1 shows which case company participated in which phase of the empirical enquiry.

Table 1. Nine enablers of lean engineering design in Engineer-To-Order projects, adopted from (Jünge et al. 2019).

Lean enabler	Definition
1. Planning commitment	Method for creating a plan of needed activities to deliver an ETO product by examining who creates the plan and how it is developed. A plan that is created through collaboration among all participating disciplines (e.g. engineering, procurement, production) generates better communication and deeper commitment within the organisation. On the other hand, when a plan is made at a higher level in the organisation, the engineer executing the activities may be unable to adjust these activities to the realities of the current working situation regarding capacity, needed information and competence. Consequently, people involved lack commitment and willingness to get involved in the planning process.
2. Planning flexibility	Method for creating, updating and re-planning needed activities to deliver an ETO product. ETO projects are known for early and ongoing involvement by the customer resulting in many changes through the ETO project. Hence, creating and updating a master plan, and replannig delayed activities as often as needed, while preparing for the next period, demands flexibility in the planning process.
3. Planning integration	Routine to evaluate the connections between the plans from different departments (e.g. procurement schedule, production plan) and organisations (e.g. delivery schedule from sub-suppliers) participating in the project. Having a clear overview of the current situation implies a firm integration of all the plans with the overall project plan.
4. Planning participation	Routine that regulates the number of meetings (where the main agenda is related to planning, controlling, and replanning) per ETO project. Participatory at such meetings is obligatory. A planning meeting is an important arena for communication and discussion about the status and potential issues to be solved. Involving all discipline in such meetings offers everybody the possibility to both be informed about what is going on in the project and to inform the rest of the organisation about eventual issues that can affect the project in the future. A project team can thus proactively work towards eliminating any constraints that might affect the project in the next period and to ensure that there are enough executable tasks as buffers.
5. Project dedication	Method used by the ETO project team to measure its performance. One of these methods is earned value management (EVM), a relevant tool for measuring the project's evolution in relation to the planned budget, time, and resources, enabling the management team to take the necessary actions and keep the project on the most favourable path. This tool is mainly useful at the management level.
6. Planning dedication	Method used for reporting the progress of planned activities. One of these methods is percent plan complete (PPC) which measures the percentage of activities completed as planned. The PPC is used as a mode to obtain involvement and commitment from all participants.
7. Replanning	Method used for replanning delayed activities. The idea is to avoid that the ETO project organisation assumes that people will execute the delayed activities as soon as possible. It is important to consider the consequences of such delays on other activities from other disciplines.
8. Impact awareness	Routine that evaluates the decision-making process in ETO projects and how to avoid that each department optimises its own activities without considering the rest of the team. It is essential to consider the bigger picture rather than optimising individual disciplines.
9. Learning ability	Method for dissemination of experiences among different ETO projects in the organisation and among the project participants (including e.g. customers and sub-suppliers). Problems, root causes and anticipated solutions should be made visible to allow learning and improvement for the future.

Table 2. Case companies' characteristics and data collection.

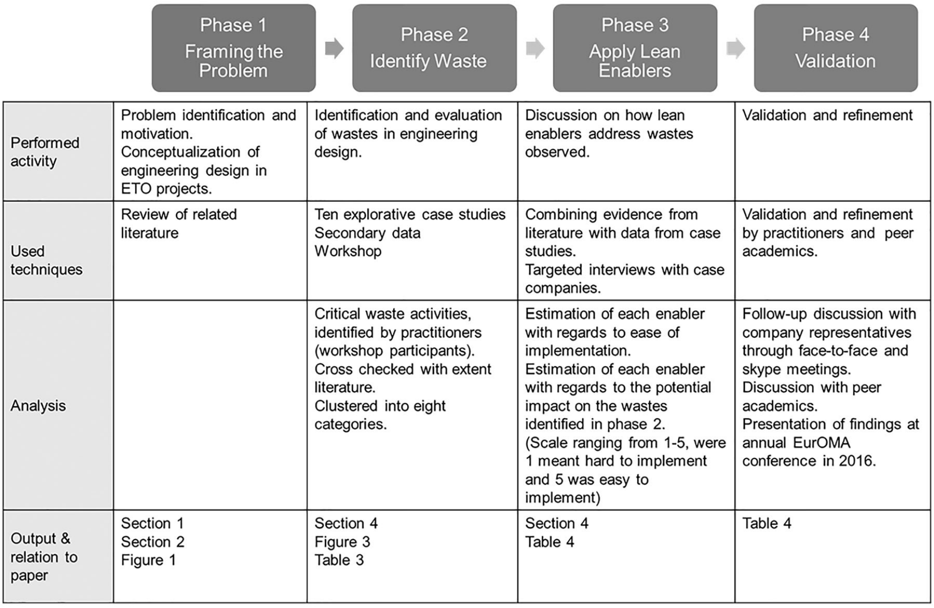
Company	Market segment	No. of employees	T/O MNOK (2016)	Project/year (no. of units sold)	Engineering (hours/unit)	No. of h with data collection	Participated in the following empirical enquiry phases (Figure 2)
A	Advanced equipment to maritime industry	>40	>180	<50	500–1.000	>50	2, 3, 4
B	Advanced equipment to casting industry	>50	>300	<50	10.000–15.000	>50	2, 3, 4
C	Advanced equipment to maritime industry	>30	>80	<20	25.000–30.000	>50	2, 3, 4
D	Advanced equipment to maritime industry	<10	>15	<50	5.000–10.000	>50	2, 3, 4
E	Advanced vessels to maritime industry	>500	>4800	<20	>50.000	>20	2, 3, 4
F	Advanced vessels to maritime industry	>300	>3700	<20	>50.000	>10	2
G	Advanced equipment to maritime industry	n/a	n/a	<100	500–1.000	>10	2
H	Advanced equipment to maritime industry	>1900	>400	<100	5.000–10.000	>50	2, 3, 4
I	Advanced equipment to maritime industry	>600	>200	<150	100–1.000	>200	2
J	Advanced vessels to maritime industry	>650	>250	<20	>50.000	>20	2

3.1.1. Phase 1: framing the problem

A review of relevant literature resulted in the conceptualising of lean engineering design in ETO projects consisting of nine enablers combining the principles from lean thinking (Ballard 2008; Emblemsvåg 2014b, Liker and Morgan 2011) agile development (Schwaber 2004) and the plan-do-check-act cycle (Deming 1986) as presented in (Jünge et al. 2019)

3.1.2. Phase 2: identify waste in ETO projects

To improve the understanding regarding how and why wastes exist in ETO projects, three researchers collected the data, comprising of semi-structured interviews, on-site observation and direct participation in meetings (Table 2). The interview guide, comprising of twelve questions, was distributed to the case companies prior to the interview. The aim of the interviews was to understand the engineering design environment of the case company and to get a better overview of the main challenges concerning planning and control of the involved participants and activities to be executed. The involved researchers strengthened the collected data by holding a workshop for several ETO companies that specifically focussed on identifying waste within engineering design processes which are in line with (Morgan 1996) recommendations. Workshop participants were employed in either engineering, project management, -project planning or top management. At the beginning of the workshop, participants were given a thorough introduction to the concept of waste



	Phase 1 Framing the Problem	Phase 2 Identify Waste	Phase 3 Apply Lean Enablers	Phase 4 Validation
Performed activity	Problem identification and motivation. Conceptualization of engineering design in ETO projects.	Identification and evaluation of wastes in engineering design.	Discussion on how lean enablers address wastes observed.	Validation and refinement
Used techniques	Review of related literature	Ten explorative case studies Secondary data Workshop	Combining evidence from literature with data from case studies. Targeted interviews with case companies.	Validation and refinement by practitioners and peer academics.
Analysis		Critical waste activities, identified by practitioners (workshop participants). Cross checked with extent literature. Clustered into eight categories.	Estimation of each enabler with regards to ease of implementation. Estimation of each enabler with regards to the potential impact on the wastes identified in phase 2. (Scale ranging from 1-5, were 1 meant hard to implement and 5 was easy to implement)	Follow-up discussion with company representatives through face-to-face and skype meetings. Discussion with peer academics. Presentation of findings at annual EurOMA conference in 2016.
Output & relation to paper	Section 1 Section 2 Figure 1	Section 4 Figure 3 Table 3	Section 4 Table 4	Table 4

Figure 2. Four phases of data collection and analysis.

and the eight waste categories as defined by (Rossi, Morgan, and Shook 2017). Then, workshop participants were asked to identify critical examples of waste activities for each of the eight categories. Koskela, Sacks, and Rooke (2012) argue for the benefits of creating a list of waste drivers, which would be instrumental in creating awareness about major waste types occurring in construction (in this present case study, engineering design), as well as mobilising actions towards stemming, reducing and eliminating waste. Thus, the next step entailed discussing the delineated waste activities in plenum with the involved participants and ranking these according to their importance).

3.1.3. Phase 3: apply lean enablers

Once the prioritised list of waste activities in engineering design was established, targeted interviews were conducted to explore if and how the lean enablers by Jünge et al. (2019) could reduce the identified wastes in engineering design. A checklist matrix based on Miles et al. (1994) was used for this purpose, following an aggregated case study methodology (c.f Childe 2011). At the beginning of the interview, participants were first given a brief 25 min lecture on lean engineering, ensuring a common understanding of terms and definitions. Participants were asked both to evaluate the ease of implementation of the particular enabler, ranging from 1 to 5, where 1 meant hard to implement and 5 was easy to implement; and to evaluate the potential impact of the enabler on the wastes identified in phase 2. Again, scores ranged from 1 to 5, where 1 meant low impact and 5 high impact on reducing waste.

3.1.4. Phase 4: validation

Follow-up discussion with company representatives through face-to-face and skype meetings, as well as discussion with three peer academics, supported the validation of the case findings and conclusions. As an example, preliminary findings were presented and refined (Junge, Kjersem, and Alfnes 2016).

3.3. Data validity and reliability

As emphasised by scholarly literature, a multiple case study approach enhances the validity (Eisenhardt 1989). From early 2015 through 2016, a research team of four academics conducted this study, improving its creative potential, which allowed the convergence of observations to strengthen the confidence in the findings (Voss, Tsikriktsis, and Frohlich 2002). Following Yin's (2014) recommendations for data collection a research protocol and a case study database were used to ensure data reliability. For triangulation purpose, this study also included the meeting minutes, the workshop presentations and company documents as sources of evidence.

4. Case findings and analysis

This section covers the research findings and analysis.

4.1. Iterative engineering design

The collected data provide a deeper understanding of how ETO projects achieve customisation through an iterative engineering design process. As mentioned, it is challenging to measure and quantify waste as either a purely non-value-adding or non-value-adding-but-necessary type. This is especially true for this context, where companies often deliver products that are part of a larger system (e.g. an oil rig) and depend on an engineering design approach, which is open to changes throughout the whole project. The analysis shows that the number of iterations varies according to the degree of integration among the participating disciplines, the project's complexity and size, and the project organisation's size. An implication of such iteration structures concerns the time frame (i.e. the length of iterations). For most of the case companies, their iterative processes could last from a few hours to several months, depending on the number of participants, disciplines and changes.

Regarding, the changes, instead of reducing complexity throughout the engineering design process, this type of 'welcoming changes' increases complexity, and more often than not, leads to inefficiency and wastes from a process perspective. Despite this notion, all case companies have a clear consensus in arguing that opening up to change implementations/change orders is a pure necessity in this market, as their degree of flexibility has huge impacts on their competitive advantage and their financial performance.

4.2. Key wastes in ETO projects

In its broadest sense, waste is any activity that absorbs resources but creates no value. This section presents ETO-specific waste found in the cases and discusses how to understand them in the ETO context. The case analysis shows that waiting, over-production, over-processing, defects and movements as the most common wastes in engineering design. Table 3 summarises wastes grouped into categories

Table 3. Engineer-To-Order specific wastes as found in engineering design.

Waste in product development	ETO specific examples	Empirical evidence (observation / quotation)
1. Waiting Waiting for work to be completed by a previous process or person.	Waiting for information from external and internal stakeholders. Waiting for successors. Waiting for technical input or decisions.	1.1. Waiting for information and/ or approval from classification societies, customer and 3rd-party approval companies. 1.2. Waiting for calculations from other people and departments, such as procurement. 1.3. Activities are uncoordinated, or planned minimal degree of concurrence and, dependence of activities when planned.
2. Over-production Producing more, faster, or at an earlier stage than is required by the next process (or customer).	Making calculations and analysis that are unnecessary because of project similarities or too early when information is immature. Over-specifying tolerances. Over-specifying functionality. Keeping busy.	2.1. Job packages that describe in detail each piece of assembly. This was demanded from one customer and became a habit for all future projects. 2.2. Mechanical engineering over-specifies functionality to compensate for suppliers' tendency to deliver under agreed tolerance. 2.3. Over specifying capacities due to earlier projects or an engineer's personal preferences. 2.4. Starting activities prior to the planned date, which leads to poor coordination and hence wrongful output
3. Over-processing Performing unnecessary processing on a task.	Getting too excited. Keeping busy. Stuck in habits. Too detailed purchasing (specifying solutions and not functionality). Silo-thinking. One-fits-all approach.	3.1. Engineers are too creative and give more than customer wants. 3.2. Drawings contain too many details. 3.3. When resources are available, drawings are checked several times. 3.4. Pre-starting activities prior customer requirements are finalised to save time or use idle capacity. 3.5. Solutions chosen based on prior experience and preferences, neglecting the specific projects requirements. 3.6. Specifying purchased components too detailed, instead of using components within approval range as delivered by suppliers. 3.7. Not analysing potential impacts on downstream activities, leading to wrong outputs. 3.8. No matter if the project (task) is supposed to be delivered fast, cheap or with upmost quality – the approach is always the same.
4. Defects Any kind of correction, such as late engineering changes.	Wrong information. Incomplete information. Mistakes. Rework. Allowing changes. Resource utilisation.	4.1. Delivering wrong drawings due to misunderstanding or lack of coordination. 4.2. Making assumption due to incomplete customer specifications. 4.3. Choosing wrong material, sub-components or forget elements. 4.4. Wrong calculations based on wrong assumption. 4.5. Correcting wrong information leading to rework, scrapping, revisions and check. 4.6. Starting activities too early – quality of information is decreased and needs to be redone. 4.7. Rework due to changes.
5. Movement Excess movement or activity during task execution	Stop and go. Bi-lateral working. Wrong in – Wrong out.	5.1. Sharing same resources on multiple projects leading to stop and go activities and unnecessary 'hand overs' when other resources need to pick up tasks from others. 5.2. Instead of organising the work through effective meetings, people meet one on one and make decisions that are not sufficiently discussed in the team. 5.3. Chasing a plan that is wrong in the first place due to poor updating efforts.
6. Transportation Movement of documents/ information/tasks	Handovers	6.1. Hiring of external engineers increases training need. 6.2. Lack of system integration that leads to manual information transfer and doubling of information.
7. Inventory Buildup of more information than is needed.	Designs in progress. Early start.	7.1. Incomplete design due to customer termination. 4.2. Designs that are not considered. 7.3. Designs are put on hold because other projects were more urgent. 7.4. Starting on documents that cannot be completed
8. Unused employee creativity Failing to develop and/or utilise human capabilities.	One-fits-all approach. Contracts that specify functionality and not solutions. Lack of transparency.	8.1. Reusing the same design that worked last time. 8.2. Employees just answer to a contract and do not engage in finding the best possible solution. 8.3. Employees do not know enough about the status of other activities which could limit their creativity, rationality and memory.

as defined by Rossi et al. (2017). To allow a deeper understanding of how wastes emerge in engineering design, the table includes a selection of quotes and/or phrases from the interviews.

First and foremost, the waste of waiting came from waiting for information, calculations, approvals, decisions, and so on. Although waiting was avoidable through better coordination, there was some waiting that was arguably less avoidable. For instance, drawings needed to be sent to independent authorities for approval. These authorities had set processing deadlines. However, case C experienced less waiting for approvals when the same employee of the approval authority was regularly used as a contact person. A key issue here is about the effect of waiting on other wastes, as it is supplemented with the second and the third wastes – over-processing and over-production, respectively.

Second, the waste of over-production was also evident in ETO projects. All case companies reported starting activities prior to plan dates, leading to poor coordination and hence the wrong output. While this waste avoidable, drawings for long lead-time items needed to be released early to assure the project's overall deadline would be met, a risk that ETO companies should take.

Third, over-processing clearly translated well into the ETO context. Compared with traditional production, engineering design is unbounded and adjustable, meaning that both start and end points, determining a project's specification range, can easily be changed. All cases showed examples where the ETO companies extended the specification range, without the customer asking for it. For instance, employees were too creative and gave more than the customer paid for, or the drawings contained more details than necessary. To cite another example, the solutions were based on prior experience and preference, rather than the current specifications. Case C showed over-processing due to a one-fits-all process, meaning regardless of whether the project was supposed to be delivered fast, at low cost or with topmost quality, the task execution approach was always the same. Furthermore, over-processing waste was associated with silo thinking. In case C, senior engineers used their experience as a means of power or a way to come up with solutions to problems at hand, based on a mere gut feeling. Although such decisions could be fruitful and speed up decision processes, they were not based on facts, with too little time was spent on considering the effects on related and downstream activities.

The fourth waste category refers to defects and rework. As shown in previous sections, the time frame of a project, especially the length of iterations, represents itself as an inherent factor in the non-value-adding activities discussed in this study. This is in line with Oehmen and Rebentich's (2010) classification of three waste categorizations derived from what they refer to as time pressure. First, time pressure entices people to take short cuts and ignore established processes and best practices, thus leading to defects. Resorting to quick fixes and patchwork is preferred over finding and fixing error sources. Second, time pressure leads to large information inventories and increases the probability of working on defective or outdated data. Third, besides the psychological effect of stress that elicits errors, time pressure forces people to pass on information that has not been verified or where the person in charge is uncertain about its quality. Although the majority of the case companies agreed on this categorisation, case C argued for the opposite, when explaining that the projects with short, allocated time were those that they managed to deliver most efficiently (in terms of quality, profitability, and resource utilisation). Furthermore, although changes generate rework, in the ETO context, allowing changes is part of the business model that outperforms those of more rigid competitors. Additionally, cases A–E showed that a high focus on resource utilisation leads to several wastes, including defects. In some cases, the researchers observed engineer utilisation of 100%. High utilisation was presumably difficult to avoid, especially in small companies.

The fifth and the sixth wastes referred to movement and transportation, respectively. The small-l and the medium-sized companies had limited access to engineering capacity. The engineers worked on several projects concurrently, making stop-and-go (switching task and focus) an unavoidable way of working. In case C and I, engineers worked on up to 5 projects at the same time. In other cases, engineering capacity was increased by hiring external engineers. Although extra capacity helped in smoothing out uneven demand, it increased the need for handovers and training, expressed as transportation waste. The lack of system integration also led to manual information transfers and doubling of information. Many of the cases considered the process of generating a plan as wasteful; therefore, it was often neglected. The authors would argue for the contrary. Although things change often, planning is inevitable. The aim is not to produce the 'perfect' plan, but to understand the current situation and prepare for the future by identifying possible constraints and solutions.

The seventh waste category expressed itself in the form of inventory. For instance, work in progress increased as designs were not considered or put on hold. As expected, the case analysis showed that waste in ETO projects was driven by uneven workloads and inconsistent demand. By failing to balance demand unfair pressures were put on processes and people, as a result causing the creation of surplus inventory and other wastes. Moreover, unevenness causes overburden, expressed as unnecessary stress to employees and processes, triggering wastes, such as defects and movement. An interesting notion is that none of the representatives of the case companies mentioned large information inventory as a potential reason for waste. Advances in data collection and analysis could potentially lead to information inventory overload. This notion confirms the fact that although technology exists, the operationalisation of data management technology is still in its infancy. In the future, information accessibility and utilisation may allow competitive advantage for organisations; nevertheless, due to strict contracts in ETO projects, information transfer from one project to others might be restricted.

The eighth and final waste category is that of unused employee creativity. For instance, case A pointed out the lack of transparency of other ongoing activities in the project as a hindrance to utilising a group's potential capacity for creativity, rationality, and knowledge-storage. To cite another example, some contracts specified a solution but not functionality, resulting in employees that answering merely to the contract and did not engage in finding the best solution.

4.3. Impacts of lean engineering design

By integrating evidence from the literature, interviews, workshops, and discussions with experts in the field, this study gains both conceptual and empirical insights in assessing the lean enablers' impact on the observed key wastes in engineering design in ETO projects. To illustrate these findings, Table 4 presents the overall assessment of the case companies' opinions and experiences regarding the impacts of lean engineering design. The left column includes the waste examples as found in the engineering design derived from the cases, while the top row includes the nine enablers of lean engineering design as defined by (Jünge et al. 2019). The score is calculated by multiplying the ease of implementing the enabler (ranging from 1 = hard to implement to 5 = is easy to implement) with the impact of the enabler on the observed waste (ranging from 1 = low impact to 5 = high impact on waste). The product of probability (i.e. ease of implementation) and impact on reducing waste generates a score between 1 and 25, enabling the authors to rank the chosen approaches. The consideration of both impact on waste and ease of implementation, allows the creation of a risk-based approach to implementing lean engineering design. The enabler with the highest score (risk) will have the highest probability of reducing waste and vice versa. In the context of this paper, this risk-based approach can offer several implications for managers implementing lean in engineering design in ETO projects. These implications are presented in Section 5.3.

5. Discussion: lessons learned

This section presents the research implications. Three themes emerge from the case studies. First, engineering design in ETO projects is done iteratively within a complex network where flexible change management of specifications (customer value) is a prerequisite for competitive advantage, allowing many possibilities for waste generation. Second, wastes in ETO are very context specific, depending on whether or not the activities are value-adding. Some of the key wastes are the results of unsynchronised efforts of designers, developers, engineers, procurement and production managers, suppliers and customers. Third, the analysis indicates that the nine lean enablers by Jünge et al. (2019) can reduce some of the observed wastes in the case companies.

5.1. Effects of iterative engineering design on waste generation

Data analysis makes it evident that efforts in improving engineering design are not first and foremost directed towards reducing the number of iterations *per se* but towards improving the iteration process and managing its impact on downstream activities. This indicates that the cost of iterations increases at the later stage of the project where they occur. Consequently, allowing a higher frequency of iterations is preferable at the earlier stage (Hoque, Akter, and Monden 2005; Sehested and Sonnenberg 2010).

Another important issue when investigating the length and the number of iterations with regard to the level of integration among different disciplines is its impact(s) on knowledge requirements and innovation. This notion is closely related to Liker and Morgan's (2019) argument, emphasising that companies should aim to identify and hence preferably fill as many knowledge gaps as possible during the first phase of engineering, also known as front-end loading. Indeed, in major projects, the main project is commonly preceded by a front-end engineering design (FEED) project.

The present study's empirical data show different needs for creative freedom at various stages of the ETO project, particularly if FEEDs have not been performed. However, the data also indicates that at the early stages, such as the conceptual and the basic design stages, the rate of innovation is high, whereas too much innovativeness at the later stages may cause disruption and delay (waste) (Ballard 2000). As such, one of the key factors influencing whether an iteration creates value or waste is the project stage when the iteration is triggered.

As visualised in Figure 3, engineering design iterations indicate the progression through levels of understanding as the designer/engineer discovers and responds to new information about a problem or a solution, as defined by Adams, Turns, and Atman (2003). Hence, the later the iterations occur, the larger the likelihood of waste generation.

Despite that all case participants' acknowledgement of the negative impacts of the high level of changes, especially during the late phases, they also encouraged it through variation orders (VOs), which often occurs as modifications or improvements after the design freeze. Thus, VOs not only emerge at late stages of the project. Some types of modifications are included in the contract and need to be covered by the company handling the ETO project, while other modifications must be paid for by the customer. Interestingly, several of the companies deliberately withheld information about modifications or suggestions for improvement during the conceptual and the basic design phases (prior to the design freeze) because they could trigger VOs later in the project that might bring added compensation. For instance, in case A, it was mentioned that VOs accounted for up to 40% of the original contract value, making VOs lucrative opportunities to realise higher profit margins. Another interesting finding about why the companies chose to withhold improvement suggestions prior to contracting was that it would serve as a means to get back on track if schedule overruns- or adverse events would occur. Nonetheless, from

Table 4. Lean enablers and their probability of waste in engineering design.

ETO waste examples/9 enablers of lean engineering design Score = ease of implementation x impact of reduction on waste	Planning participation	Planning dedication	Re-planning ability	Planning integration	Project dedication	Impact awareness	Learning ability	Planning commitment	Planning flexibility
Sum	488	248	234	228	200	194	180	180	159
1.1 Waiting for information and/ or approval from classification societies, customer, and 3^{rd}-party companies.	12	4	3	4	12	2	2	2	6
1.2 Waiting for calculations from other people and departments, such as procurement.	20	12	3	10	12	10	2	2	3
1.3 Activities are uncoordinated, or planned with minimal degree of concurrence and dependence of activities when planned	20	12	15	10	4	6	6	10	12
2.1 Job packages that describe in detail each piece of assembly, demanded form one customer and became a habit for all future projects.	12	4	3	8	8	6	6	4	3
2.2 Mechanical engineering over-specifies functionality to compensate for suppliers' tendency to deliver under agreed tolerance.	12	4	3	10	4	8	6	6	3
2.3 Over specifying capacities due to earlier projects or an engineer's personal preferences.	16	4	6	10	12	8	10	6	3
2.4 Starting activities prior to the planned date, which leads to poor coordination and hence wrongful output	12	20	9	10	8	6	6	10	9
3.1 Engineers are too creative and give more than customer wants.	12	16	3	10	4	10	4	2	3
3.2 Drawings contain too many details	12	4	3	10	4	10	4	2	3
3.3 When resources are available, drawings are checked several times.	12	12	3	4	4	4	4	2	3
3.4 Pre-starting activities prior customer requirements are finalised to save time or use idle capacity.	12	4	3	4	8	6	4	8	3
3.5 Solutions chosen based on prior experience and preferences, neglecting the specific projects requirements.	16	8	3	8	4	8	10	8	3
3.6 Specifying purchased components too detailed, instead of using components within approval range as delivered by suppliers.	12	4	3	8	4	10	6	4	3
3.7 Not analysing potential impacts on downstream activities, leading to wrong outputs.	16	4	9	10	20	10	10	10	3
3.8 No matter if the project (task) is supposed to be delivered fast, cheap or with upmost quality – the approach is always the same.	12	4	3	6	12	6	10	4	3
4.1 Delivering wrong drawings due to misunderstanding or lack of coordination	20	8	3	10	4	8	10	6	3
4.2 Making assumption due to incomplete customer specifications.	20	8	12	4	4	4	4	4	3
4.3 Choosing wrong material, components or forget elements.	16	4	12	8	4	8	4	6	3
4.4 Wrong calculations based on wrong assumption.	16	4	12	8	4	6	2	6	3
4.5 Correcting wrong information leading to rework, scrapping, revisions and check	12	4	15	10	4	4	2	6	6
4.6 Starting activities too early – quality of information is decreased and needs to be redone.	12	8	9	6	4	4	2	6	3
4.7 Rework due to changes.	12	4	12	4	4	4	2	4	12
5.1 Sharing same resources on multiple projects leading to stop and go activities and unnecessary 'hand overs'	20	4	3	6	8	6	8	8	6
5.2 Instead of organising the work through effective meetings, people meet one on one and make decisions that are not sufficiently discussed in the team.	20	8	9	6	4	6	8	10	6
5.3 Chasing a plan that is wrong in the first place due to poor updating efforts.	20	16	15	8	4	4	4	8	15
6.1 Hiring of external engineers increases training need.	8	4	3	2	4	2	2	2	3
6.2 Lack of system integration which leads to manual information transfer and doubling of information.	20	8	15	10	4	6	8	6	12
7.1 Incomplete design due to customer termination.	4	4	3	2	4	2	2	2	3
7.2 Designs that are not considered	16	4	3	2	4	2	2	2	3
7.3 Designs are put on hold, because other projects are more urgent.	12	4	3	2	4	2	6	8	3
7.4 Starting on documents that cannot be completed.	12	12	9	4	4	2	4	2	3
8.1 Reusing the same design that worked last time.	8	4	3	2	4	2	8	2	3
8.2 Employees answer to a contract and do not engage in finding the best possible solution.	12	4	6	2	4	6	6	4	3
8.3 Employees do not know enough about the status of other activities which could limit their creativity, rationality, and memory.	20	20	15	10	4	6	6	8	3

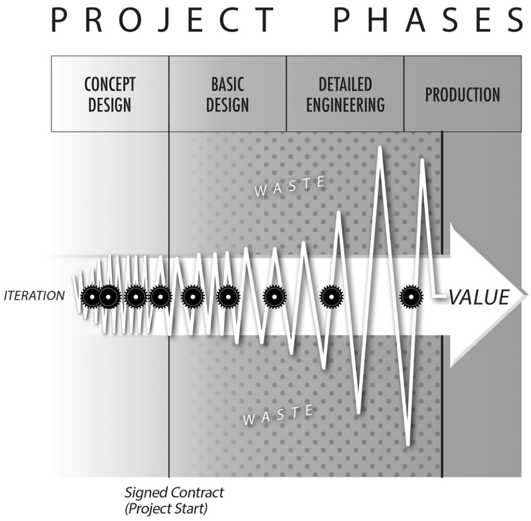


Figure 3. Iterations at different stages in an Engineer-To-Order project.

a lean perspective though, such hiding or delaying of known opportunities for change and improvement should not be encouraged. However, echoing the contractual regimes under which the companies operate, see Emblemsvåg (2020), there can be various reasons for this behaviour, normally triggered by the nature of the contractual regime and how this has been exercised by the customers in earlier projects. In a sense, the customers have reaped what they have sowed.

Although these results confirm the association between iterations and waste generation, the main intention behind iterations is to create value for the customer in a development environment where specifications, constraints and possibilities are explored and defined stepwise throughout the project. The picture that emerges from the analysis is that iterations can be classified into three groups. First, from a product standpoint, iterations can increase or decrease the product's economic. Second, from a single company perspective, iterations can increase learning for future projects or waste by ignoring the opportunity for improvement. Third, from an ETO project organisation (involving many companies) perspective, iterations can improve its communication ability and contribute to tighter integration of project partners. However, whether an iteration creates value rather than waste seems to be little controlled or understood by the involved practitioners. Many questions remain unanswered regarding how iterative engineering design should be managed to maximise its value generation.

5.2. Engineering design generates waste

The case analysis provided a reason to argue that waste was related to unsynchronised efforts of designers, developers, engineers, employees engaged in the procurement, engineering, production, and so on. As this may not be different for other project-based operations, such as construction or software development, several possible explanations of wastes related to poor synchronisation can be found by synthesising the waste discovered with ETO-specific characteristics. For example, ETO projects were often undertaken by many partners separated by geographical distance, meaning that the process of development, production and final assembly could be done in different parts of the world, which could easily lead to misunderstandings, the extra need for coordination or even rework. Second, the ETO products in this case study were mainly maritime items, where technical drawings had to obtain independent, third-party approval, leading to non-value-adding-but-necessary-waiting. Third, once production had fully started, engineering personnel had been assigned to new/other projects, making wastes related to waiting and rework evident.

The involved researchers have encountered several case companies with a low level of willingness to systematically measure waste in engineering design, which could possibly be related to the engineers' perception of systematic waste control that could jeopardise their professional freedom to exercise creativity. Furthermore, some of the wastes were highly person dependent and affected by the employees' prior experience or type of educational background, influencing their choices on how to develop a design, how to interpret a customer's specifications, or the level of involvement with others when making decisions. It is also important to acknowledge that the presented list of wastes is not exhaustive. Finally, the ETO-specific examples derived from the case study were not exclusive to one waste category but were placed in the most evident category to avoid duplication and increase readability.

5.3. Waste reduction through lean engineering design

The analysis showed how each enabler assisted in eliminating waste. This section presents the lessons learned, following the sequence of the highest to the lowest ranked enabler regarding the probability of reducing waste.

5.3.1. Planning participation

This enabler scores the highest (488), meaning that it has the highest impact on reducing waste and is considered easier to implement than other enablers (e.g. planning commitment and impact awareness). This enabler regulates the frequency of holding and participating in planning meetings. During the planning meetings, all information from all departments (internally and externally) meet the customer requirements and the as-is world. Importantly, these meetings need to be tailored to each project. Too loosely structured meetings can easily be time consuming and ineffective (Kjersem 2020). The meeting is not over until the participants agree on what to do, leading to more realistically planned activities and thus contributing to reducing waste/e.g. 1.2. Waiting for calculation from other departments, and 8.3. Limited employee capacity and creativity). This view is consistent with that of AL-Qahtani and El Aziz (2013), who mention that unless a collaborative and encouraging environment is established, knowledge will not improve product development capability.

5.3.2. Planning dedication

This enabler assists in keeping track of actual progress. In earlier studies on ETO companies, Adrodegari et al. (2015) and Jünge et al. (2015) have found that the act of monitoring and measuring actual progress versus planned progress is a neglected practice in engineering. Only by knowing where a project team is in relation to where it should be can adjust its activities for the next period. The measurement of the percentage of activities completed as planned can act as a motivator for involvement and commitment to assisting in minimising wastes (e.g. 2.4. Activities are started prior to the planned date, which leads to poor coordination and hence wrongful output).

5.3.3. Re-planning ability

This enabler refers to the routines for re-planning activities. When new activities occur (e.g. due to changes or defects), planned activities need to be replanned, including considering the consequences of such changes or delays for other activities from other disciplines. As such, this enabler is considered to reduce waste (e.g. 1.3 Uncoordinated activities that are planned with minimal degree of concurrence and dependence when planned; and waste 4.5. Waste related to correcting wrong information, leading to rework, scrapping, additional revisions and controls). In other words, planning should be connected to checking and acting, meaning that only if the status of planned activities is checked, and re-planned when necessary, can realistic progress be achieved.

5.3.4. Planning integration

This enabler incorporates all project disciplines into one common plan and is regarded as having a very high impact on waste reduction (with a total score of 228), although difficult to implement (with a score of 2). Despite the importance of integration, none of the participating companies has systems in place that integrated plans from all disciplines. A possible reason for this is the fact that an ETO project organisation consists of many different disciplines from both internal and external departments, challenging the sharing and integration of plans. Production plans are often quite detailed, while design and engineering plans are less detailed or non-existent, making it difficult to align interdependent activities. This situation is especially disastrous when engineering and production are carried out concurrently (Mello, Strandhagen, and Alfnes 2015). Therefore, this enabler recommends establishing routines for integrating plans from all disciplines. Regarding new, project-specific participants, possible integrations need to be identified in the beginning of the project. Furthermore, the case analysis finds it preferable to start sharing available plans, even if they are in a wrong format (need manual adjustment) or are based on estimates (need updates). Incremental improvements make integration easier and shared data more updated over time. Therefore, planning integration assists ETO project organisations in reducing wastes (e.g. 3.2. Drawings contain too many details, 2.3. Over-specifying capacities, 4.1. Delivery of wrong drawings, and 7.2. Manual information transfer and/or doubling of information).

5.3.5. Project dedication

This enabler refers to the method used by the project team to track its performance. The empirical data show that the most used tool for measuring project performance is earned value management (EVM), which measures the project's evolution in relation to the planned budget, time and resources. While EVM provides top management with a useful early indication of how the project's overall performance, planning dedication and replanning should be taken care of to avoid EVM's measurement of activities that do not give value to the project and are rather wasteful. Combining these three enablers called an integrated EVM system (Jünge et al. 2019). It means that all disciplines measure progress on both an overall project level (EVM) and on a discipline level, considering how planned activities and actual performance impact affect other disciplines' activities. Hence, as confirmed by the analysis, the enabler project dedication reduces the likelihood of some wastes (e.g. 3.7. Wrong output due to a lack of analysis of impacts on downstream activities).

5.3.6. Impact awareness

This enabler evaluates the decision-making process in ETO projects and how each discipline or department optimises its own activities without considering the rest of the project team. In ETO projects, many decisions need to be made based on incomplete information; therefore, including all disciplines when estimating the potential impact is recommended. This will raise awareness of the possible outcomes and prepare participants to act accordingly. Furthermore, necessary changes in contracts or agreements can be discussed proactively. Consequently, this enabler is considered to reduce waiting, (e.g. 1.2. Waiting for calculations) and over-processing (e.g. 6.3. Too specific details on purchased components).

5.3.7. Learning ability

This enabler focuses on sharing learned lessons among all employees and external stakeholders (e.g. customers and suppliers) and affects many waste categories, particularly over-processing and overproduction. Elaboration on what succeeds and what fails lies at the heart of lean practices because only in this way can continuous improvement be possible. At the same time, establishing routines for sharing problems, root causes and anticipated solutions among all project participants is difficult, resulting in an ease of implementation score of 2. It is important to focus on reflection and learning, not putting the blame on somebody.

5.3.8. Planning commitment

This enabler refers to the method of creating an initial project plan, including the needed activities to deliver an ETO project. ETO project organisations need to involve the *doers of each activity* when planning. When plans are drawn without including all participants, such as the person who will actually execute a planned activity, unrealistic activities will be defined and backed up with low commitment, making delays unavoidable. On the contrary, this enabler reduces some wastes (e.g. 2.4. Defects due to starting activities earlier than planned and 6.2. Additional handovers and movement due to ineffective meetings and unsynchronised decisions).

5.3.9. Planning flexibility

This enabler regulates the method of updating the project plan. ETO projects are known for the customer's early and ongoing involvement, resulting in many changes throughout the entire project period. Hence, creating and updating the plan as often as needed, while preparing for the next period, demands flexibility in the planning process. Moreover, a well-functioning updating method ensures that the planned activities remain valid according to stakeholder requirements. Therefore, it is recommended that companies establish routines for updating the project plan and visualising the planned activities. Only if the plan is updated and shows a true picture of the situation would project participants use it and commit to it. Dedicated resources need to be established and trained. Hence, this enabler reduces the probability of some wastes (e.g. 4.5. Unnecessary rework and 6.3. Chasing a plan that is wrong in the first place. This view is consistent with the finding of Ward and Sobek (2007) and Womack and Jones (1996) that information is only valuable if useful; valuable information reduces the risk of producing an unsatisfactory product or performing a superfluous development activity.

6. Conclusion, limitations and suggestion for future research

Undoubtedly, designing, engineering, and manufacturing customised, highly advanced equipment constitute a complex and demanding exercise, but above all, it is an iterative process. No single person in an ETO organisation has all the information or the authority needed to push progress throughout a project's lifecycle. Iteratively, information needs to be gathered, analysed, discussed, verified and used to meet requirements and constraints set by material, technological, legal, environmental and human-related considerations. Hidden risks of waste-generating activities lurk along this path of iterations. Thus, the motivation behind this research is based on the practical problem of extensive waste in ETO projects. Moving a step further than simply presenting existing wastes, the concept of lean engineering design and its potential for waste reduction are presented.

In line with the literature section, the authors find compelling evidence that the time when iterations occur, modifications or improvements after the design freeze, and time pressure are important factors contributing to waste generation. It seems possible that the generally accepted business practice of welcoming changes throughout the project, specifically contributes to additional iterations. As this practice is considered a major source of competitive advantage over others, the recommendation is not to aim at keeping a low number of iterations but to pay attention to when and why iterations occur and how they can be speeded up. Equally important is the utilisation of learning and risk-reduction opportunities that can be found during iterations. As ETO projects are notoriously known for their uncertainty, the results give room for drawing a connection between the efficiency of iterations management and reduction of risk. It means that even if iterations may generate waste during a given iteration round, they can also significantly reduce risk, which can be considered as a dominant contributor to value generation.

This case study of ten ETO companies reveals movement, waiting, over-production, over-processing and defects as the most common wastes in engineering in ETO projects. Additionally, wastes are highly person dependent, meaning that prior experience or type of education influences the engineer's choices on how to develop a design, how to interpret customer's specifications, or how much to involve others when making decisions affects the chances of waste during an iteration. All cases provide evidence that a lean approach to engineering design has a positive impact on the waste reduction. The enabler *planning participation* is ranked as having the highest probability to reduce waste.

The rationale behind the efforts of identifying, defining and minimising waste in engineering design is based on this assumption: if companies are able to identify the types of wastes, they generate, then they can find a way to remove those wastes by using lean tools, and by doing so, gain competitive advantage. For this reason, the proposed lean engineering design approach allows ETO project organisations to gather, discuss, evaluate and eventually transforms information into value. As a result, knowledge gaps are identified and filled at an early stage. Although lean engineering design may require operational adjustment and potential increases in short-term costs, the long-term benefits are indisputable.

The preceding discussion makes it apparent that the presented results fill a literature gap and extend researchers' and field experts' knowledge with the following contributions:

- Offer significant and original insights into wastes found in engineering design, from both practical and academic perspectives, by establishing a generic list of defined wastes identified in ETO projects. Comparable to the eminent list of seven wastes in production, as defined by Ohno (1988) over 30 years ago, that inspired practitioners and academics to identify wastes in production, hopefully, the presented list of wastes in engineering design can equally inspire practitioners and academics to identify similar wastes in their companies or projects.

- Provide managerial implications by describing how lean engineering design allows balancing between the negative impact of iterations (e.g. waste) on downstream activities and the potential benefits of the iterative process (e.g. learning for the future or improving the integration among project partners). As such, this paper contributes to strengthening critical engineering management skills by offering a set of recommendations that ease the differentiation between value-adding and non-value-adding iterations. Oehmen and Rebentich (2010) point out that systematic action is necessary to reduce waste. It is therefore arguable that improving an engineer's skills and motivation in working in a lean environment, where project participants draw plans in coordination with one another and make decisions based on frequently updated information, will reduce the number of situations that can lead to waste. The suggested enablers focus on frontline workers and their capability to solve problems. By doing so, ETO project managers avoid pushing decisions on others but rather enable the frontline workers (e.g. lead engineer) to make quicker and more committed decisions.
- Demonstrate the applicability of waste reduction approaches (as found in lean literature) to ETO projects by applying lean engineering design. This is an important contribution, as previous research has predominantly focussed on industries producing either very large products, such as the aerospace industry (Oppenheim 2011; Reinertsen 2005), or a large amount of products, such as the automotive industry (Oliver, Schab, and Holweg 2007; Ward and Sobek 2007). To the authors' best knowledge, waste reduction approaches in engineering design, as found in ETO, have not been discussed in any lean or engineering management literature.

6.1. Limitations and suggestion for future research

This research has some limitations due to the nature of the sample used in this multiple case study. The case companies are located in western Norway, and their answers might thus be linked to regional issues. This point may be relevant because recent data from 24 countries suggest that the implementation of lean principles highly depends on cultural aspects (Kull et al. 2014).

Decisions allow progress in ETO projects. Information is needed for making decisions. This empirical investigation provides some reasons to believe that the quality or the *maturity* of the information shared within an iteration affects the quality of the iteration. In other words, project participants either make a decision based on the available information and push progress forward or continue/extend the iteration to gather more mature information before making a final decision. It seems to be a crucial managerial (and organizational) capability to standardise the process of judging maturity. It is certainly context specific; nonetheless, the authors believe that project organisations would benefit from a holistic standardised procedure and thus recommend it and welcome further research on this matter.

Moreover, the research identifies an extensive list of wastes as observed in ETO projects. Generating such a list is a critical starting point in creating awareness about major waste types occurring in engineering design, as well as mobilising actions towards stemming, reducing and eliminating waste. These interesting findings could further benefit from a comparative case analysis, which would allow linking wastes occurrence to specific cases, thus providing a more comprehensive understanding.

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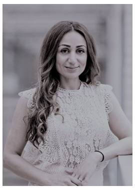

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