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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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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).

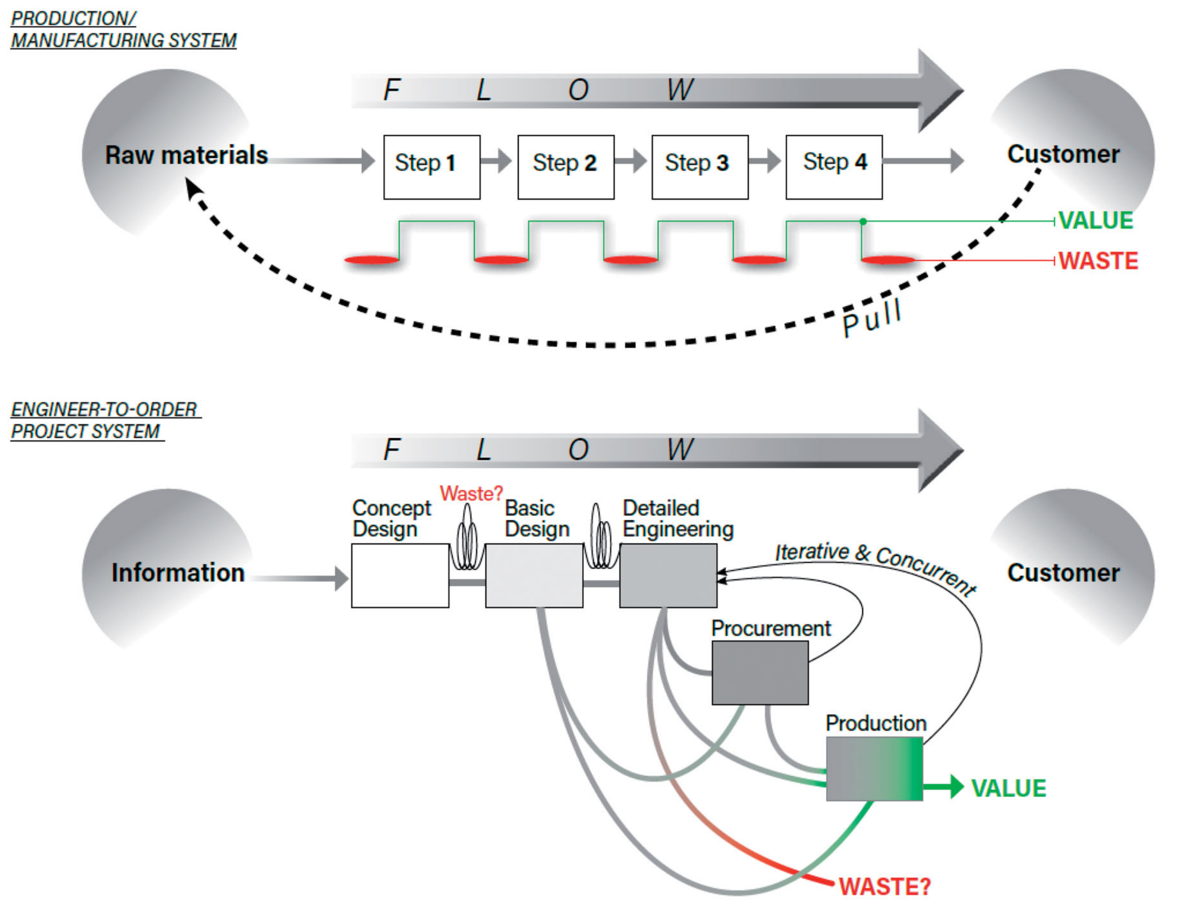

Figure 1. The value creation model as applied to Engineer-To-Order projects.

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 Sum	Planning participation 488	Planning dedication 248	Re-planning ability 234	Planning integration 228	Project dedication 200	Impact awareness 194	Learning ability 180	Planning commitment 180	Planning flexibility 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 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

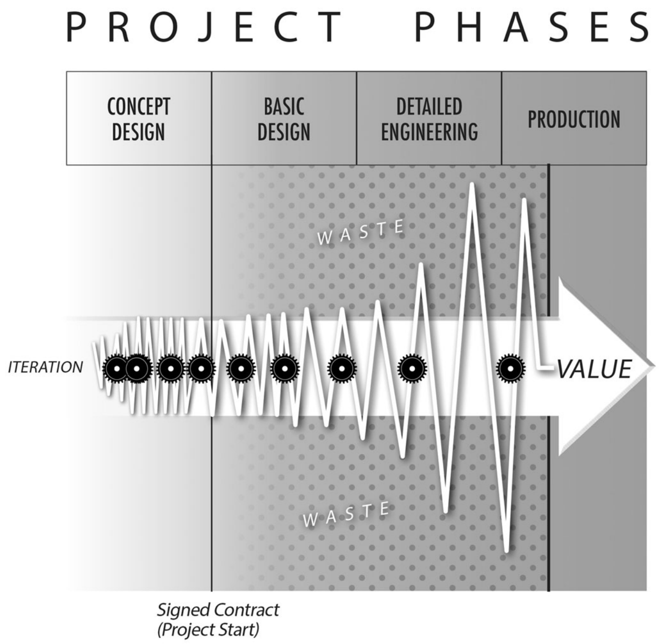

Figure 3. Iterations at different stages in an Engineer-To-Order project.

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 in 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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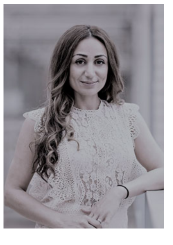

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