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# Rearticulating supply chain design and operation principles to mitigate uncertainty in the Norwegian engineer-to-order shipbuilding sector

Erlend Alfnes[a,*], Jonathan Gosling[b], Mohamed Naim[b], Heidi C. Dreyer[a]

[a] Norwegian University of Science and Technology, Trondheim, Norway
[b] Cardiff Business School, Cardiff University, Cardiff, UK

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ABSTRACT

Engineering-to-order (ETO) systems are especially prone to high levels of uncertainty in demand, as well as from internal processes, supply side sources and their own control systems. Understanding and categorising the causes of uncertainty provides an opportunity for organisations to determine the principles and tactics for their mitigation. Previous scholars have developed a framework for ETO uncertainty reduction by the extension of the established 'FORRIDGE' principles from general manufacturing management. Although such a framework is claimed to be generic, it has only previously been applied in the UK construction industry. The aim of this paper is to determine—via a replication study—the reproducibility, reliability and validity of the ETO uncertainty reduction framework and extend it. A conceptual replication research study was undertaken involving a different population sample: the Norwegian shipbuilding sector. Based on previous research, we categorise ETO into two forms: innovate to order (ITO) and redesign to order (RTO). Targeting 10 Norwegian first-tier ship equipment manufacturers, the respondents were questioned regarding their sources of uncertainty and measures they adopted to mitigate these. Supply chain tactics for shipbuilding have been identified and mapped against the ETO uncertainty reduction principles and uncertainty sources for RTO and ITO types of ETO. Our study has highlighted the reliability of the FORRIDGE principles. We extend the original set of tactics established in the construction sector so that the ETO uncertainty reduction principles can be used in another sector, and we indicate the significance of different tactics for ITO and RTO types of ETO. We make a methodological contribution by showing the application of a conceptual replication research design in an operations management context. Further research is required to test the principles in other ETO-intensive sectors.

## 1. Introduction

In contrast to other forms of production, where products or services are designed and then manufactured for mass or segmented markets, engineering-to-order (ETO) systems aim to satisfy the requirements of a specific customer or client on a 'one-to-one' basis. Often, ETO systems are associated with 'first/one-of-a-kind' products, in which the associated production is managed and controlled as a project. Therefore, the associated supply chains are temporary or are a highly adaptable constellation of enterprises. The performance metrics associated with ETO include the degree of customisation and project delivery schedule and budget adherence (Cannas et al., 2020; Bjomo et al., 2022). Unlike other forms of production, where the development and production terrain is more predictable, ETO systems often require innovation to cope with a highly uncertain environment in which there is a considerable degree of risk. The typical ETO industry sectors include construction (Dallasega et al., 2019), aerospace (Telles et al., 2020), defence (Hicks et al., 2001), capital goods (Hicks and Braiden, 2000) and shipbuilding (Iakymenko et al., 2020).

In other forms of manufacturing-based production, there are well-known and developed means to mitigate the effects of uncertainty; this is done by applying established principles of good practice based on classic work in systems dynamics and smooth material flow controls (Towill, 1997). The literature in this area builds on legacy knowledge developed in industrial dynamics, control theory, manufacturing systems research and a rich body of empirical and experiential work to improve manufacturing systems to develop an integrated set of guiding 'FORRIDGE' principles, where FORRIDGE refers to the historical

* Corresponding author.
*E-mail addresses:* erlend.alfnes@ntnu.no (E. Alfnes), GoslingJ@cardiff.ac.uk (J. Gosling), NaimMM@cardiff.ac.uk (M. Naim), Heidi.c.dreyer@ntnu.no (H.C. Dreyer).

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synthesis of work from John Burbidge and Jay Forrester (Towill and Gosling, 2014). To translate such know-how into ETO situations, Gosling et al. (2015) established six principles with inherent associated tactics to address uncertainty within the empirical context of the construction sector; they tentatively proposed that the principles and tactics were applied in other ETO contexts but that further empirical work was needed to substantiate these claims, particularly by “using different research methods, and additional research in other ETO sectors” (Gosling et al., 2015).

Since then, the body of knowledge on ETO has progressed, for instance, in the specific understanding of complexity factors (Birkie and Trucco, 2016), as well as suitable tactical planning processes (Shurrab et al., 2022). However, despite the growing interest in ETO forms of production, the underlying principles for their management and control are not well defined, and an integrated approach with a robust evidence base has yet to emerge. Debates regarding the appropriate design and operation approaches are still unresolved. In a review of ETO-specific research between 2010 and 2020, Cannas and Gosling (2021) suggested that the issues of which manufacturing solutions should be adopted, adapted or rejected in ETO settings should be an area of ongoing debate for the next decade. In addition, there is a need for further cross-sectional industry studies.

In general, ETO sectors have been found to be profoundly affected by uncertainty (Gosling et al., 2013; Birkie and Trucco, 2016; Alfnes et al., 2021), and recent evidence from ETO shipbuilding has identified the systemic factors that inhibit effective and efficient delivery (Alfnes et al., 2021). Complex ships are technologically advanced products with demanding design requirements. In this context, uncertainties in ETO shipbuilding may occur from the demand side (e.g., contracts that allow customers to make changes throughout the entire delivery process), within internal processes (e.g., technically complex engineering and production involving new materials, methods and extensive customer involvement), from the supply side (e.g., last minute engineering changes causing delays from suppliers), and product delivery planning and control systems (e.g., coordination of the interface between the different disciplines working concurrently with overlapping projects activities) (Alfnes et al., 2021). However, the solutions, change programmes and approaches to managing these systemic factors are far from clear. Gosling et al. (2015) offer a starting point that is based on a long legacy of systems research, but the extent of generalisation that is possible across ETO sectors is not yet known.

Although it is common for representatives to argue that every industry sector—and even subsector—is unique, many studies have noted the close similarities of shipbuilding with construction and their close alignment with the characteristics of ETO forms (Koskela, 1992; Gosling and Naim, 2009). ETO sectors such as construction and shipbuilding are project-based industries delivering ‘one-of-a-kind’ design solutions to customers with specific needs. The project organisation is temporary, with a purposeful design for each specific project. Here, project activities are defined by a contract and subjected to regular interruptions from classification societies (such as those found in the design of ships) and change requests from the customer (Emblemsvåg, 2020). Therefore, there is the clear potential for learning and discourse between the two industries and the potential for some interesting observations and reflections relating to the generalisability of ETO knowledge.

Building on the above, the aim of the current paper is *to determine,* via *a replication study, the reproducibility, reliability and validity of the FORRDIGE construction-based ETO principles and tactics framework developed by Gosling* et al. *(2015) in an attempt to mitigate uncertainty and extend the framework to the shipbuilding sector*. Our deductive frame of reference is ETO production, and the empirical sample is ship and offshore building, here with a particular focus on Norwegian ship equipment manufacturing, where there is a high degree of product customisation and specialisation.

In addressing the aim of the present study, our intended contribution is to establish the reliability of the six overarching principles originally articulated by Towill (1997) and later developed further by Gosling et al. (2015) that govern uncertainty mitigation in ETO supply chains. The potential generalisability of the original principles beyond construction to shipbuilding contributes to the general operations management field, where there is a dearth of replication studies. In the current study, in exploiting a more refined and systematic uncertainty approach than Gosling et al.’s (2015) investigation of ‘problems’, we also identify emergent patterns of tactics for very innovative types of projects, which offers additional insights into the initiatives that can be used by ETO organisations operating in highly innovative projects, leading to a reflection on the extent to which ETO supply chains are the same.

The structure of the present paper is as follows: The next section explores the literature on uncertainty in supply chains generally, as well as ETO types more specifically, before then examining the principles of good practices for ETO supply chains. In Section 3, the research design and replication research approach are elaborated upon, and the case studies are presented, leading to the results in Sections 4, 5 and 6. The discussion in Section 6 reflects on the contributions in relation to the literature. The paper finishes with a conclusion that provides the implications of the research for theory and practice.

## 2. Literature review

### 2.1. Uncertainty management in supply chains

Uncertainty can be defined as ‘deviation from the unachievable ideal of completely deterministic knowledge of the relevant system’ (Walker et al., 2003). These deviations mean that organisations along the supply chain develop coping strategies, such as increasing inventory and/or capacity, that often increase costs, yet the supply chain is still liable to poor performance (Simangunsong et al., 2016). In contrast, reducing uncertainty has the potential to reduce the total costs while leading to enhanced supply chain performance, such as delivery times and responsiveness to changes in demand (Childerhouse and Towill, 2004).

Identifying the causes of uncertainty is the first step in determining reduction strategies. A notable approach in doing so is known as the uncertainty circle model (Mason-Jones and Towill, 1998) wherein, taking a single organisational perspective, four sources of supply chain uncertainty are classified as process (internal), supply (from vendors), demand (from customers) and control (resulting from the planning and control of all activities). Uncertainty is typically amplified through those interactions between these different sources. The uncertainty model has been further extended and/or exploited by adding a fifth ‘environmental’ category to explain events exogenous to the other four sources (e.g., a natural disaster) (Christopher and Peck, 2004), the due consideration of the logistics triad (i.e., consigner, consignee and transportation provider) (Sanchez Rodrigues et al., 2008) and multitier chains (Wang-Mlynek and Foerstl, 2020) rather than a single focal company, and in closed-loop supply chains (Goltsos et al., 2019; Marcos et al., 2021).

### 2.2. Systemic factors creating uncertainty in ETO supply chains

ETO supply chains have been shown to acutely suffer from uncertainty factors; hence, uncertainty reduction is also desirable, such as in construction (Yang et al., 2021). The application of uncertainty management in ETO environments has been relatively limited compared with non-ETO environments. Gosling et al. (2013) applied the uncertainty circle model in the construction sector to show that timely and correct information from clients, the accuracy of the project plan and permissions from regulators were found as being the largest sources of uncertainty.

Alfnes et al. (2021) extended this work to the context of the shipbuilding sector; they used a systems approach to show the interaction of uncertainty factors across specification and design, mobilisation, production and supplier subsystems, as well as the top five sources of uncertainty in two system types. These system types, innovate to order systems (ITO) and redesign to order systems (RTO), have some characteristics that make it natural to treat them differently. A high share of value creation for shipbuilding suppliers comes from RTO systems that are repeatedly delivering products with a slightly modified design. Overengineering, configuration production lead times, a lack of common rules and production capacity were identified as the most significant factors leading to uncertainty in RTO systems. ITO systems aim to develop unique and premium-priced solutions for the customer and are distinguished from RTO by the innovation level, high number of engineering hours, close collaboration with the R&D department and long duration (typically two to three years). Specification, supplier lead times, relationship management, product structure and engineering lead times were identified as the top uncertainties.

The study presented in Alfnes et al. (2021) resulted in a method to understand the systemic contributing factors of uncertainty, including the identification, categorisation and analyses of systemic uncertainties, and this was applied to distinct ETO systems with their own attributes. Gosling et al. (2015) indicated how problems can be addressed by using the principles of good supply chain design, but they did not have access to the more sophisticated method proposed and applied to distinct ETO types by Alfnes et al. (2021); hence, we build on the findings from both studies later.

### 2.3. Principles of good practice for ETO supply chains

One potential way of addressing uncertainty is by implementing principles of 'good practice' across the supply chain. By integrating the methodologies of industrial dynamics and material flow control, a set of system operation principles was developed (Towill, 1997), which provided a foundation for 'good' supply chain design. The 'FORRIDGE' principles, a phrase derived from combining the key intellectual influences of Forrester (1961) and Burbidge (1961), were originally defined as the control system principle, time compression principle, information transparency principle and echelon elimination principle. A previously implied fifth 'synchronisation' principle was later made explicit by Geary et al. (2006). Since their publication in 1997, the principles have been shown to offer a powerful guide for engineering effective make-to-stock supply chains, but their application in ETO supply chains has been less clear.

Fig. 1, which is adapted from Gosling et al. (2015), shows the intellectual logic and background of the development of the principles for the design and operation of ETO supply chains. The solid arrows denote the flow of logic from different theoretical domains, as well as the direction of the travel of ideas. The framework highlights that the origins of the principles can be traced to systems thinking, where much of the early work flowed from systems engineering and system dynamics in manufacturing (e.g., Parnaby, 1979). These principles were then incrementally adapted and validated through various workstreams, largely from the automotive sector, and they were more recently adapted for the specific context of ETO supply chains (Gosling et al., 2015). For each theoretical domain, we also include the substantive influencing references. At the tactical level, these principles may be interpreted differently across the range of ETO industries, so there is a need to learn from specific ETO sector applications to provide feedback and a more general understanding of the principles. This learning feedback from construction and shipbuilding tactics to the ETO knowledge base and broader supply chain management discipline is illustrated by the dotted arrows at the bottom of Fig. 1.

The FORRIDGE principles were conceived of as part of a three-level model to guide good practice, which included the required vision, principles and toolbox. This was originally based on the consulting methodologies proposed by Werr et al. (1997) but then further developed via exploitation in auditing methodologies (e.g., Towill and Childerhouse, 2006) and further enriched through an application in the Toyota Production System (Towill, 2007). In translating the model into an operational environment, the vision explains the guiding beliefs, which have been argued to be a 'seamless supply chain' in a make-to-stock (MTS) context. The principles should give operational guidance, for instance, in promoting the concept of 'swift and even material flow' (Schmenner, 2001). Tools or tactics may be regarded as specific problem-solving practices, such as those related to standard industrial engineering practice or even basic 'production management' actions that are appropriate to the value stream.

The aforementioned stream of research on principles of good practice was conceived and discussed within the context of traditional repetitive, high-volume manufacturing environments, primarily in the automotive sector, which, at the time, was largely MTS. This prompts some interesting theoretical debates about how the vision, principles and tactics should be translated and interpreted in ETO sectors and situations. Gosling et al. (2015) explored the translation and adaptation of these principles within a construction empirical context. They concluded that the FORRIDGE principles could be applied in an appropriate way in ETO situations, but the extent and criticality vary. They also concluded that an additional design for X (DfX) principle was needed for ETO situations to consider the engineering and design dimensions of such supply chains. Information transparency and DfX principles were identified as the most widely applicable principles in ETO. Tactical interpretations of the principles were identified across each of the six principles, but these were grounded in the context of the

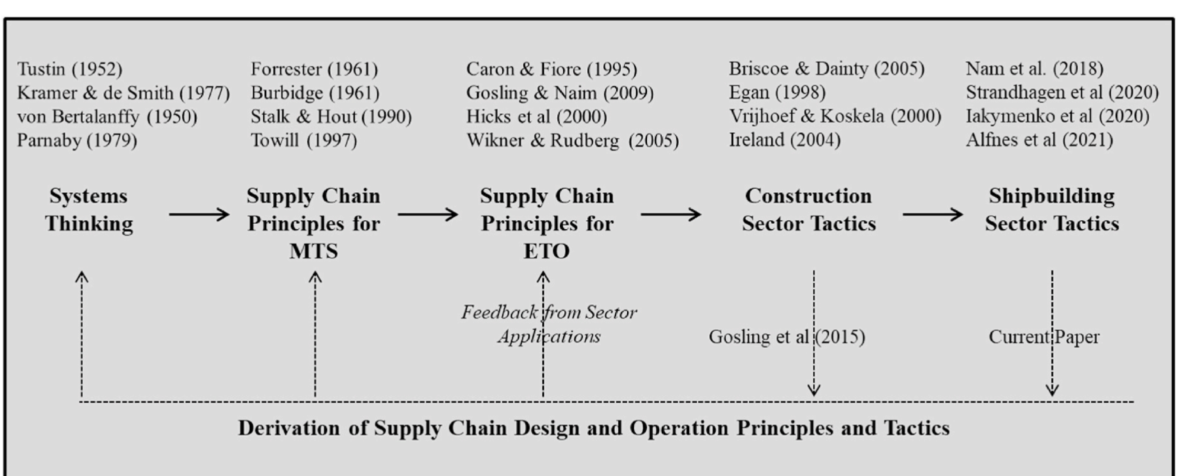


**Fig. 1.** Deriving the principles of good practice for the design and operation of ETO supply chains.

construction sector cases. The authors suggested that the tactics for ETO would need to be investigated.

Table 1 shows the principle of good practice as originally defined in Towill (1997) and later by Towill and Gosling (2014), but also with the DfX principle added by Gosling et al. (2015). Table 1 indicates the different emphases when applying and interpreting the principles in different contexts. In MTS situations, the focus is on optimising inventory and process flows for an efficient delivery system. Designs should be complete and products available for customers (Towill and Childerhouse, 2006). Based on recent research and advances in the understanding of ETO supply chains, for example the studies by Alfnes et al. (2021) and Cannas and Gosling (2021), along with the Gosling et al. (2015) study specifically focusing on the construction sector, it is possible to outline some differences regarding the emphasis when applying the principles in ETO situations, as shown in the final column in table. A notable difference is that, when operating in ETO situations and applying the principles, orders are fulfilled through project delivery systems, and design work is cocreated with a customer or client.

The current study investigates the potential application of the FORRIDGE principles within the shipbuilding sector. As can be seen from Fig. 1, while a priori knowledge gained from the construction sector exists, specific literature relating to good practice within shipbuilding is available that can inform our understanding of the potential tactics and principles, which forms the focus of the next subsection.

### 2.4. Shipbuilding and principles of good practice

The principle of time compression has been investigated in the context of shipbuilding. Semini et al. (2022) used multiple regression analysis to compare shipbuilding time based on data from 156 ship projects and found that lower levels of outsourcing, smaller ship sizes, and repeat projects all compress time. Sanderson and Cox (2008) proposed shifting the customer order decoupling point downstream for functional parts such as cables and applying a customised assembly of a basic cable components strategy. The shipbuilder Ulstein International has developed and implemented a fast-track conceptual design process and its related design toolbox to shortcut the iterative process in the early design phases (Brett et al., 2018). Mello et al. (2015) highlighted the dangers of aggressively compressing lead times via concurrent engineering and production initiatives because of expanding coordination costs. However, other researchers have found it possible to successfully remove time waste from shipbuilding processes via effective value stream mapping (Thomassen et al., 2015; Fatouh et al., 2020).

In line with the control system principle, Nam et al. (2018) noted that shipyards need better control over their internal planning systems when developing customised products. Junge et al. (2018) highlighted the need for more tailored approaches to planning and control in ETO environments, making a link with principles of good practice in project planning and control; they developed a maturity model to guide practice towards more effective project planning. Sjøbakk et al. (2015) developed a performance measurement system that systematically monitors how well materials management is carried out in an ETO supply chain. Emblemsvåg (2014) developed a lean project planning approach that has been successfully used by a shipyard to build a so-called platform supply vessel.

Addressing the synchronisation principle, Iakymenko et al. (2020) developed a generic framework with processes and tools for how ETO companies in the maritime sector can manage engineering changes that disrupt workflows across the supply chain. Praharsi et al. (2022) measured the performance of traditional shipbuilding in Indonesia by using supply chain operations reference (SCOR) metrics and proposed that an integrated synchronised ordering system with machine, welding, wood, steel and bolts and nuts suppliers is necessary to improve performance.

Linking to information transparency, numerous studies have reported the potential of different technologies to improve information

**Table 1**
The principles of good practice with a proposed emphasis for application in MTS and ETO supply chains.

| FORRIDGE principles | Original definitions (Towill, 1997; Towill and Gosling, 2014; Gosling et al., 2015). | Emphasis for application in Make-to-stock supply chains (Childerhouse and Towill, 2003; Towill and Childerhouse, 2006; Towill, 2007). | Emphasis for application in engineer-to-order supply chains (Gosling et al., 2015; Alfnes et al., 2021; Cannas and Gosling, 2021); Cannas and Gosling (2021)· |
|---|---|---|---|
| *Time Compression Principle* | Every activity in the chain should be undertaken in the minimum time needed to achieve task goals. | Stabilise processes, automate, optimise and compress to achieve minimum reasonable time. | Compress waiting times, subject to potential quality and cost implications. |
| *Control System Principle* | There is a need to select the most appropriate control system best suited to achieving user targets and taking unnecessary guesswork out of the system. | Integrated control of production volumes to avoid bullwhip and stock outs. | Integrated control of progress across projects, specific material requirements and engineering changes. |
| *Synchronisation Principle* | All events are synchronised so that orders and deliveries are visible at discrete points in time, and there is continuous ordering synchronised throughout the chain. | Enable coordinated process flows to reduce potential for 'batch and queue' to create phasing issues and unsynchronised activity. | Enable flows of project activity through sequencing and alignment of supply chain and management of contractual interfaces. |
| *Information Transparency Principle* | Up-to-the-minute data that are free of 'noise' and bias should be accessed by all members in the system. | Ensure order information (i.e. volumes) are shared throughout chain and not distorted. | Ensure that specification is clear to all parties, design and expert knowledge is shared, and progress and requirements across projects is visible to the supply chain. |
| *Echelon Elimination Principle* | There should be the minimum number of echelons appropriate to the goals of the supply chain. | Reduce the number of material or information stages and/or interfaces to minimum reasonable level. | Ensure the right organisations can contribute to projects at the right time, reducing unnecessary handovers and interfaces. |
| *Design for X Principle* | Design should be fit for purpose and enables 'right first time'. | Ensure design is ready, available and enables swift production and delivery without defects. | Embed design for manufacture/buildability from an early stage, with input from key stakeholders, and, where appropriate, configure structures and platforms to help meet customisation needs quickly. |

flows. For example, Strandhagen et al. (2020) highlighted the role of Industry 4.0 as a tactic in enabling the information transparency principle to deliver more sustainable shipbuilding supply chains. Fonseca and Gaspar (2021) investigated how cohesive digital twin ships can be used to share design information and distribute tasks among various stakeholders in the supply chain, proposing an open standard for digital twin ship data. Fraga-Lamas et al. (2018) also illustrated how shipyards have been implementing Industry 4.0 technologies to create industrial augmented reality. These applications can lead to value and improvement in quality and process control, the tracking of materials and inventory management, predictive maintenance, better communication, simplification and automation and visualisation for safety and design.

Related to the reduction of echelons to create a flow in shipbuilding, only a few publications have been published. Kjersem et al. (2015) presented a case study in which pull production concepts were used to achieve continuous flow in the case company's hull units' production, where the processes performed on each fabricated part were repetitive, even though the parts were customised. Wu and Shaw (2011) described a basic ship design process using knowledge-based engineering methods, in which all tasks in the design flow could be performed through the same interface.

Addressing the criticality of the DfX principle, but also linked with complexity reduction and echelon elimination, researchers in the shipbuilding community have shown the detrimental impact of over-complexity and uncertainty in ship design (Ebrahimi et al., 2021a, 2021b). Rehn et al. (2019) outlined and discussed the suitability of a generic method for quantifying the cost and time of making changes to design variables to support better decision making in the conceptual ship design phase. Vaagen et al. (2017) used stochastic dynamic modelling to demonstrate that flexible design strategies, such as developing designs with options to postpone design specifications, can be used to hedge against uncertainties.

## 3. Methods

Although Gosling et al. (2015) showed their findings more generally in an ETO setting, the empirical element of their study was carried out exclusively in the UK construction sector. In testing the ETO principles (Gosling et al., 2015), we have undertaken a replication study. Although replication studies are extensively used in the physical and life sciences, they are often viewed as a 'second-class' form of research in the social sciences, hence leading to a dearth of their applications (Hendrick, 1990).

The lack of replication studies is also evident in operations management (Erkul et al., 2017), despite their potential to help with generalising theories and enhancing the reliability and validity of a field of research (Hendrick, 1990; Sadikoglu and Zehir, 2010; Erkul et al., 2017). There are various forms of a replication study, including strict, partial and conceptual (Hendrick, 1990). Strict replication involves exactly replicating the original study in terms of the variables and method adopted, perhaps even including the same data set or population. A partial replication will involve a relaxation of some aspects of the original study with respect to the method and data set, but the population remains the same. A conceptual replication adopts not only a different approach, but also a different population with the aim of validating, generalising and, maybe, modifying the original theoretical premise (Hendrick, 1990; Erkul et al., 2017).

Hendrick (1990) undertook a comprehensive review of the three forms of replication studies, which Erkul et al. (2017) exploited in their explanation of the various nuances of the three types. The main advantage of strict replications is that, if they are successful, then they validate the original theory and the method previously adopted, but there is no new learning generated. The advantage of the partial and conceptual replications is that they provide an opportunity to extend the original theory, leading to new insights and innovation. In addition, conceptual replications have a considerable scope when it comes to generalising an existing theory and maybe revising the theory. Of course, if strict replication does not produce the same results, then there can be doubt regarding the original study's method and, hence, the theory itself. Or conversely, it may lead to doubt regarding the rigour of the replication study. This may then lead to a discourse in the scientific community. Partial and conceptual replications are seen as risky endeavours because they yield little new knowledge if they are unsuccessful in validating or generalising the original theory.

The differences between the previous study (Gosling et al., 2015) and our approach are summarised in Table 2. In our study, we have adopted a conceptual replication approach wherein we not only have a different population, namely the Norwegian shipbuilding sector as opposed to the UK construction industry, but we also apply different methods and forms of analysis in determining the sources of uncertainty and testing the relevance and credibility of the ETO principles.

Our study and that of Gosling et al. (2015) employ an overall deductive and inductive research approach. Gosling et al. (2015) founded their study on the FORRIDGE manufacturing principles for seamless material flow (Towill, 1997) and employed and modified them based on the literature on construction supply chain management. They then juxtaposed industrial practices for the mitigation 'problems' identified in the construction supply chain, here based on a set of interviews from organisations involved in two different construction projects. This analysis involved categorising mitigation tactics according to each of the principles before aligning them to the problems identified. Similarly, in the present paper, we have exploited the construction ETO principles (Gosling et al., 2015) as a foundation for our empirical research. Our interrogation of the 'problems' given in Gosling et al. (2015) indicates that such problems may be categorised according to the different sources of uncertainty given by the 'uncertainty circle' model (Mason-Jones and Towill, 1998) and that they can be extended to consider ETO in shipbuilding (Alfnes et al., 2021). Hence, our approach to the analysis is more nuanced and systematic, exploiting the concept of uncertainty.

Although Gosling et al. (2015) considered the construction industry as a homogenous whole, in the present paper, we have developed the principles according to two different ETO types: ITO and RTO (Alfnes et al., 2021). ITO projects involve complex engineering activities, such as the development of codes, standards and principles to develop new products, and they are part of the R&D programme for the company. These projects can take years and require a huge amount of engineering hours. RTO projects involve more routine engineering activities to design detailed product specifications or modify existing designs for a range of similar projects. These are repeat projects with shorter durations and few engineering hours compared with ITO.

The cases included in the present study were selected according to the two ETO types. Gosling et al. (2015) conducted interviews to determine the mitigation tactics for any foreseen problems, here as determined by the interviewees. In the present study, we have undertaken a more systematic approach. The primary data collection activity was company-specific workshops with 10 suppliers in the shipbuilding industry (Table 3). The invited participants were managers from the engineering and operations departments. The analytical phases of the research protocol were as follows: determine the focus products, ascertain and evaluate sources of uncertainty, identify and categorise tactics and determine the applicability of principles and tactics to the uncertainties identified. The sources of uncertainty were discussed, and a consensus was reached as to how they could mitigate uncertainties, either as identified by Alfnes et al. (2021) and/or as they themselves recognised from their experiences, for each of the two ETO types (ITO and RTO). The company participants also determined the extent to which the uncertainties identified impacted their organisations. Once the participants had given their own tactics to reduce or eliminate uncertainty, they were asked if they had considered other mitigation tactics, here as identified from the literature. This involved a discussion in the workshop as to the merits of various mitigation approaches.

We included questions in the interview protocol to allow the

**Table 2**
Contrasting our conceptual replication research approach with the original ETO theory building.

| Attributes of the research methods adopted (based on Hendrick, 1990) | Original (Gosling et al., 2015) | Conceptual replication in this paper | Comments on conceptual replication approach |
|---|---|---|---|
| *Population* | UK construction sector | Norwegian shipbuilding | Shipbuilding has similar, but also some different, characteristics compared with construction. Norwegian shipbuilding in particular has a high degree of product customisation and specialisation, as found in construction. |
| *Assumption about the ETO process* | Homogenous ETO | Heterogenous ETO – ITO and RTO | Advances the 'one-size-fits-all' approach of the original ETO study. |
| *Research approach* | Deductive and inductive | Deductive and inductive | The overall research strategy is maintained, even though there are differences in population and forms of data collection and analysis. |
| *Deductive element* | Builds on the manufacturing FORRIDGE principles (Towill, 1997) | Exploits the construction ETO principles (Gosling et al., 2015) | Indicates the progression and advancement of the original 1997 and 2015 studies. |
| *Empirical inductive element* | Interrogating interviewees' approaches to mitigating problems in a homogeneous ETO process | Interrogating interviewees' approaches to mitigating uncertainty in heterogenous ETO system | Opinion based sources but with more nuanced interrogation of different forms of ETO, allowing for more considered and refined principles and tactics to be determined. |
| *Analysis* | Align theoretical principles and underlying tactics to the real-world problems | Align theoretical principles and underlying tactics to the real-world uncertainties | A more systematic consideration is given to different forms of uncertainty rather than a catch-all 'problems'. |
| *Unit of analysis* | Two different networks for two different construction projects | A sample of first-tier suppliers | First-tier suppliers are involved in multiple networks providing the opportunity to build on breadth of varying experiences. |
| *Data collection method* | Interviews | Workshops | Rather than individual responses there is opportunity for debate, discourse and consensus. |
| *Number of companies* | Nine in Network 1 and three in Network 2 with no cross-over | 10 first-tier equipment manufacturers supplying to different markets | Less of a focus on particular projects while instead providing a wider range of market characteristics to be captured, and generalisation is improved. |
| *Size of companies* | 20–44000 employees | 50–3500 employees | This is within the range of the original population. |
| *Research agents* | Four academic researchers with expertise in 1. manufacturing systems and who was the sole author of the FORRIDGE principles paper 2. construction management, especially in the UK sector 3. engineer-to-order supply chains with a focus on construction 4. business systems engineering with cross-sector applications | Four academic researchers with expertise in 1. manufacturing planning and control, especially in the Norwegian shipbuilding sector 2. supply chain management across different industry sectors 3. as per Gosling et al. (2015) 4. as per Gosling et al. (2015) | This balances continuity and know-how from one study to the next, but also provides for new skills and knowledge and avoids bias by the original research agents. |

interviewees to identify sources of uncertainty and the principles and tactics to mitigate them. This allowed the research team to code the linkages between uncertainty sources, principles and tactics. These proposed linkages were reviewed by the interviewees and refined using any further feedback to increase the validity. A final classification of whether the tactics were loosely or closely connected to uncertainty sources was undertaken by the research team.

The companies in each of the specific workshops are characterised in Table 3. The total number of companies selected—and, hence, the final number of workshops—was based on data saturation, that is, the point when no additional insights are gleaned, for example, any new tactics identified, by consecutive workshops (Saunders et al., 2018).

The case companies in Table 3 are first-tier manufacturers that deliver different types of equipment to ships. All companies are based in Norway, but the main market is sale to international customers. A common competence is engineering, and the typical disciplines are mechanical, electro, hydraulic, systems and automation engineering. The companies manage the entire set of supply chain activities, but the level of outsourced activities varies between them. Company A has outsourced physical activities such as production and is mainly undertaking engineering and supply chain management, companies B, D, F and G do their own assembly, and companies C, E, H, I and J have in-house fabrication.

The main business in most companies is RTO projects. The product portfolios in four of the companies (E, F, H and J) also include a large share of standard products. The most extreme is company J, where 88% of the volume is standard. RTO projects are based on established product models that require minor modifications and are delivered repeatedly. The annual volumes of RTO projects in a product family typically range from 20 to 300 in our sample, and each project has a project duration of 6–12 months. The size and, hence, the required engineering effort for

**Table 3**
Summary of company and product characteristics.

| Case | Employees | ETO type | Subsectors | Projects/ year | Duration (months) | Engineering hours/ project | Participants |
|---|---|---|---|---|---|---|---|
| A Ship cranes | 100 | RTO | Fishery equipment | 50–100 | 13–24 | 50–100 | Head of operations |
| | | ITO | Electrical winch system | 1 | 9 | 10000–20000 | Head of engineering |
| B Power technology | 230 | RTO | Maritime power thruster | 25–30 | 6–10 | 250–750 | Head of production Head of execution |
| | | ITO | Subsea power grid system | 1 | 36 | 8000–10000 | |
| C Propulsion systems | 100 | RTO | Tunnel thruster | 20–30 | 6–18 | 150 | Chief operating officer |
| | | ITO | Propulsion system | 1 | 13–24 | 10000–20000 | Vice president of projects |
| D Ship interior | 50 | RTO | Cruise interior | 1 | 12 | 5000 | Chief operating officer |
| | | ITO | Cruise interior | 1 | 24 | 20000 | Technical engineer |
| E Lightning systems | 3500 | RTO | LED linear light fitting | 30 | 13–24 | 4 | Factory manager Technical manager Head of projects |
| | | ITO | Fish farm lighting | 10 | 24–36 | 2000 | |
| F Sensor systems | 120 | RTO | Wear monitoring system | 180–280 | 4 | 10 | General manager supply chain General manager projects |
| | | ITO | Tank measurement system | 5 | 8 | 10000 | |
| G Engine systems | 150 | RTO | Generator set | 100 | 8–14 | 100–250 | Commercial director (also responsible for engineering and operations) |
| | | ITO | Low vibration generator set | 0–1 | 24 | 5000 | |
| H Hydraulic systems | 150 | RTO | Winch block system | 500–1000 | 2–3 | 10–20 | Executive vice president systems |
| | | ITO | Active dampening systems | 0–1 | 18 | 2000 | Vice president technology Vice president sales & tender |
| I Winch systems | 90 | RTO | Anchor handling systems | 5 | 12 | 2000 | Chief technical officer Chief operating officer |
| | | ITO | Mooring systems | 1 | 12 | 4000 | |
| J Sewage treatment systems | 190 | RTO | Sewage treatment plant | 45 | 3–5 | 10–80 | Production director Technical director |
| | | ITO | Not applicable | Not applicable | Not applicable | Not applicable | |

RTO systems will vary. Companies I and D deliver large systems for entire ships with thousands of components, requiring thousands of engineering hours, but typically, RTO systems only require tens or hundreds of engineering hours.

In contrast, ITO projects are delivered in low volumes and are part of the research and development process in the case companies. The designs from ITO projects are often reused as RTO projects afterwards. ITO projects are predominately initiated in-house, and customers are involved during or after the concept design phase. Contract-based engineering in ITO projects still requires thousands of hours and often lasts for two to three years.

## 4. Uncertainty sources

This section presents the exploitation of the project types and uncertainty sources identified in Alfnes et al. (2021). The lists of uncertainty sources for RTO and ITO systems were presented to the respondents, and they were asked to comment and rank them. Generally, the respondents confirmed the original findings from Alfnes et al. (2021), but the ranking of the uncertainty sources varied. The top five uncertainty sources identified for RTO are presented in Table 4.

RTO projects deliver mature products with limited customisation. For these projects, the main uncertainty sources that hinder performance are specification, supply chain coordination, lead times, production capacity and configuration. Specification is the most important uncertainty source, with a major concern being that unclear customer requirements and technical complexity make it challenging to decide the right price on the design adjustments requested by the customer. This is especially the cause because a *'lack of detail in specification allows the customer to do late design changes and delay delivery dates, which can cause surprises and interface problems in engineering'* (chief operating officer in Case C). Because of the global supply chain crisis, supplier lead times have increased, making it the second most important uncertainty source. The executive vice president of Case H describes this as follows: *'Availability of critical components and materials is a major uncertainty source. A typical project has components and materials that are sourced globally from 40 suppliers, so the risks of delay of on one component for a project is high'*. Cross-functional coordination is challenging because task interdependency is high, and several interfaces and handovers interrupt the flow from contract to delivery. Often, several engineering disciplines are involved in the delivery process. The chief operating officer in Case A states, *'We have four engineering disciplines that need to merge before final assembly and testing; this is a major source of uncertainty'*. The two least important uncertainty sources for RTO projects are available production capacity and a lack of configuration rules. The criticality of production capacity depends on the level of outsourcing.

**Table 4**
The cases' uncertainty profile for RTO systems.

| RTO Uncertainties | Cases | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J |
| Specification | *** | * | ** | *** | ** | *** | *** | *** | *** | * |
| Supplier lead times | ** | *** | * | * | ** | ** | *** | *** | ** | *** |
| Cross-functional coordination | *** | * | *** | ** | *** | ** | ** | ** | ** | * |
| Production capacity | – | *** | ** | – | *** | – | – | * | * | *** |
| Configuration | ** | – | – | – | ** | – | * | * | * | * |

***Highly important ** Important * Less important – Not important.

For example, this is not a concern for Case A because production is outsourced, while Case B is doing advanced electro installation in-house and is very concerned about production capacity. The criticality of configuration rules depends on product complexity; simple products are easier to configure. The technical manager for Case E explains, *'We are developing product configurators for simple standard products, not for slightly more complex RTO products'*.

All cases, except for J, have had experience with ITO projects, confirming the uncertainty sources identified by Alfnes et al. (2021). The main uncertainty sources that hinder excellence in ITO projects are specification, relationship management, engineering and supplier lead times and lack of product structures. Specification is also the most important uncertainty source in ITO projects. The head of execution for Case B explains, *'In such projects, the specification is not complete, the customer and R&D are involved in all phases, and technology is developed, tested and adapted during the entire project period'*.

The uncertainty sources for ITO projects are given in Table 5.

The high level of innovation, customisation and complexity makes it difficult to capture customer requirements and understand technological challenges at an early stage. The head of projects for Case E gives an example to illustrate this: *'A main challenge in the project was the open and unclear scope and specification when the project started. As the system evolved, it became more and more complex during the project, particularly the complexity of the system automation part. Technically, the project was a success but without much profit'*. Relationship management and communication are not sufficiently intensive and rich to ensure that the sufficient competencies are included, and mutual understanding is created in the supply chain. The general manager for supply chains in Case F is concerned about communication and states, *'There is a lack of common understanding in the supply chain. Different actors have different views of what the contract specifies the final product to be'*. The engineering of innovative products involves numerous iterations and handovers that can be very time-consuming. The general manager for engineering in Case F acknowledges this, but also states that *'there is a need to improve ownership for customer requirements and ensure timeliness by all departments, including R&D'*. The chief operating officer in Case I explains how engineering and supplier lead times are related: *'We use too much time on engineering (e.g. because of a lot of uncertainties) and have to short time for suppliers'*. A lack of product structure is also an issue because *'no existing complete structure exists for this kind of project. The structure must be invented, and it is important to see the critical issues in the structure; this requires experience'* (Chief technical officer Case I).

## 5. Principles and tactics

During the workshops, a range of established tactics were identified to tackle uncertainty and improve performance for ETO projects. These tactics have been previously synthesised and categorised by researchers using the extended FORRIDGE principles developed by Gosling et al. (2015). The tactics established for RTO also support ITO projects. Hence, ITO projects benefit from the same tactics as RTO projects, but because of their complexity and higher levels of uncertainty, companies have established additional tactics that are mainly related to how people work and interact in such projects. The list of tactics identified and how they relate to the existing five principles identified by Gosling et al. (2015) are given in Table 6.

The first group of tactics relates to the principle of time compression (P1), meaning that processes should be achieved in a minimum, reasonable time. Sales *specification assistant systems* that are based on design templates from earlier projects are used to guide the customer and structure data collection. *Automation* in engineering, production and purchasing operations also helps compress cycle times. *The modularity* of a major share of the product structure enables the engineer to mix and match sets of standard design elements while reducing the cycle times in engineering. Unique long lead-time items are purchased for each project at the handover from sales, while standard components are picked from

**Table 6**
The tactics identified for RTO and ITO projects and their categorisation within the principles.

| Principles | RTO tactics | Additional ITO tactics |
|---|---|---|
| P1 Time compression | Product specification assistant system (A, C, E, F, G, H, I, J)<br>Automation (B, C, E, I, H)<br>Modular platform (B, D, E, F, G, H, I, J)<br>Component inventory (B, C, F, G, H, I, J)<br>Subcontracting (A, C, I) | Predesign analysis (A, F, G, H, I)<br>Agile methods (B, C, E, F) |
| P2 Control system | Sales & operations planning (B, C)<br>Material requirement planning (B, C, E, F, H, I, J)<br>KPI systems (B, C, D, E, H, I) | Centralised cross-disciplinary project team (A, E, F) |
| P3 Synchronisation | Stage gate execution model (A, B, C, D, E, F, G, H, I)<br>Standard contracts and procedures (C, F, H, J)<br>Supply chain coordination meeting (A, F, I, J) | Risk-sharing contracts (A, D, E, F, J) |
| P4 Information transparency | Enterprise resource planning systems (B, C, D, E, F, G, H, I, J)<br>Product life cycle management systems (C, F, H, I)<br>Forecasting (C, F, H, J)<br>Project planning system (A, C, D, G, H, I) | Design integration event (A, C, G, H)<br>Knowledge transfer between projects (B, C, D, F, G, I) |
| P5 Echelon elimination | Defined roles and responsibilities in projects (A, C, D, E, F, H)<br>Handover review and testing (A, C, F, I, J)<br>Framework agreements (all)<br>Accreditation of suppliers (all) | Cross-disciplinary innovation events (C, F) |
| P6 Design for X | Design for Manufacturing/ Service (B, C, E, F, G, H, I, J)<br>CAD/CAM (all)<br>Product templates (A, C, E, F, G, H, J) | Early customer and supplier involvement (A, B, D, E, F, G, H, I)<br>Prototyping (A, B, C, E, H)<br>Computer-aided modelling and simulation (A, G, H) |

**Table 5**
The cases' uncertainty profiles for ITO systems.

| ITO uncertainty sources | Cases | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J |
| Specification | *** | *** | * | *** | *** | *** | *** | *** | *** | |
| Relationship management | *** | ** | *** | *** | ** | ** | ** | ** | *** | |
| Engineering lead times | * | *** | *** | ** | * | * | *** | *** | *** | |
| Supplier lead times | ** | * | * | ** | * | * | * | * | ** | |
| Product structure | ** | * | ** | – | * | – | * | * | * | |

***Highly important ** Important * Less important – Not important.

the *inventories* that serve several projects and ensure timely deliveries. Standard components are input for new products or sold directly as spare parts. However, it is difficult to determine the appropriate capacity and inventory levels because of the uncertain demand in shipbuilding supply chains. *Subcontracting* of production, typically machining and detailed engineering, is used to handle demand peaks. For ITO projects, *predesign analysis* and requests for information procedures are established to obtain detailed information about the product environment as soon as the contract is signed. *Agile methods* and design sprints are used to compress the cycle times in engineering after handover from sales.

The second group of tactics relates to the control systems (P2) of the supply chain to manage the flow of materials and information efficiently and effectively, along with the utilisation of people and equipment to respond to customer requirements. The methods developed for manufacturing, such as *sales and operations planning* and *material requirements planning,* are common. Some have established overall *KPI systems* that show the deadlines and status across several projects. In ITO projects, which are often large and complex and require their own project organisation, a *centralised project planning team* is established to coordinate all the internal and external disciplines that are involved.

The tactics in the synchronisation principle (P3) aim to organise all events so that the orders and deliverables are visible at discrete points in time. *Stage gate execution models* are established to ensure that everybody is aware of milestones, such as review meetings, test events, handover meetings, and delivery dates across the entire project portfolio. Contracts are *standardised* to enable clear design specifications, tasks, deadlines and responsibilities. Procedures are standardised to support more predictable workflows in engineering, testing and production. *Supply chain coordination* meetings with project managers, engineering, production and purchasing are regularly arranged to clarify issues related to delivery times and task synchronisation. In ITO projects with high uncertainties, *risk-sharing contracts* are established with suppliers and/or customer to allow for the necessary changes during the project without a loss of commitment to the plan.

The next cluster of tactics relates to the information transparency principle (P4). Information-sharing tactics are established through software systems for *enterprise resource planning (ERP), product lifecycle management (PLM)* and *project planning*. These systems are supported by data capturing systems in physical operations such as fabrication, assembly, logistics, testing and installation. *Forecasting* is used to predict the demand for standard components and support inventory management. ITO projects that build new product structures, articles and design items cannot fully exploit software systems, such as ERP, that require predefined master data. Instead, such ITO projects rely more on *design integration events* to improve the communication between different engineering disciplines and to sort out technical interface problems and procedures for *knowledge sharing between projects.*

The tactics also relate to the principle of echelon elimination (P5), which reduces the number of handover and interface issues as much as possible. Several cases have established a procedure to clearly *define the roles and responsibilities* for each project. Quite a few have assigned project leaders and a single point of contact that will follow a project through all phases. It is also common to have a *handover* procedure to manage the reassignment of projects between disciplines in the workflow, typically from sales to engineering and from engineering to production and supply. All cases have *accreditation* and *framework agreements* with suppliers to improve supply performance. In ITO projects, some have established cross-disciplinary *innovation events* for communication and problem solving with people from the entire supply chain.

The next group of tactics can be described as DfX (P6). These are tactics that ensure the designs are right the first time and fit for the purpose, for example, for manufacturing, assembly, installation, operations and/or service. The participants especially emphasised the importance of involving experienced operators to make *designs for better manufacturing and service* operations. Software for *computer-aided design* and *computer-aided manufacturing* are used to execute engineering efficiently without quality defects. This software can help to embed DfX in the specification stage. *Standardised design elements* and *template bills of materials* are used to improve the efficiency and quality of engineering work. For ITO projects, *early customer and supplier involvement* ensures commitment to the development process already in the sales phase. Computer-aided *modelling* and *analysis*, or physical *prototypes*, are used to involve all relevant supply chain actors in the testing and enable improvement of product performance at an early stage as a way to ensure that customer specifications are adequately captured and translated into a viable product design.

## 6. Mitigating uncertainties

The different elements of the study from Sections 4 and 5 are combined in Tables 7 and 8. The tables map the principles and tactics against the uncertainty sources for RTO and ITO projects. The potential links are indicated by the coloured blocks, where dark blocks signify a strong linkage between uncertainty sources and tactics/principles, where the lighter shaded blocks indicate moderate links, and where there is no shading, in which a link is not established.

Table 7 illustrates how different tactics and principles can tackle uncertainty and improve the performance for RTO projects. Most tactics have been identified for cross-functional coordination, followed by specification and supplier lead times. These three uncertainty sources are also considered the most important. Information transparency and time compression tactics appear to have the most comprehensive applicability to the uncertainties identified in the present paper.

Table 8 illustrates the interaction between tactics/principles and uncertainties for ITO projects. The ITO project tactics come in addition to those tactics identified in Table 7 and are used to handle uncertainties that are inherent in innovative projects. Most additional tactics have been identified as reducing engineering lead times, followed by specification and supply chain relationship management. These three uncertainty sources are also considered the most important. DfX tactics seems to be the most important way to handle uncertainties in ITO projects.

## 7. Discussion

The present research was initiated with the aim of replicating Gosling et al.'s (2015) work to determine the appropriate design and operation principles for supply chains in the construction sector but with a particular focus on Norwegian ship equipment manufacturing, where there is a high degree of product customisation and specialisation. Our main interest was to determine the reproducibility, reliability and validity of the construction-based ETO principles and tactics framework. The important points flowing from this research are the extent to which ETO principles and the associated tactics of good practice differ between ETO and non-ETO systems and the extent to which they extend across ETO sectors and forms.

The current study distinguishes between two archetypes of ETO projects—RTO and ITO—that represent different positions regarding engineering and production subflows (Cannas et al., 2020). Our case studies have identified specification as the most important uncertainty for both types of projects, even if both types differ in engineering intensity. This is in line with earlier studies on the impact of specification and design uncertainty on performance in shipbuilding supply chains, such as Vaagen et al. (2017). However, the implications of specification uncertainties differ for the two project types. For RTO, to a large extent, the technology is known, but cost estimation is challenging because the margins are small and a minor tweak for the design can result in an economic loss. For ITO, the margins are higher, but the technology is less mature and design requirements that seem negligible might imply major technology development activities and delays.

**Table 7**
Principles, tactics and uncertainties RTO.

| Principles | RTO tactics | Uncertainty type | | | | |
|---|---|---|---|---|---|---|
| | | Specification | Cross func. Coordination | Supplier lead times | Production capacity | Configuration |
| P1 Time compression | Product specification assistant system | ■ | | | | ■ |
| | Automation | | | | ■ | ▒ |
| | Modular platforms | ■ | | | | ■ |
| | Component inventory | | | ■ | ▒ | |
| | Subcontracting | | | | ■ | |
| P2 Control system | Sales & operations planning | | ■ | ▒ | ■ | |
| | Material requirement planning | | ■ | ■ | | |
| | KPI systems | | ■ | | | |
| P3 Synchronisation | Stage gate execution model | | ■ | | | |
| | Standard contracts and procedures | ■ | ■ | ▒ | | |
| | Supply chain coordination meetings | | ■ | ■ | ▒ | |
| P4 Information transparency | Enterprise resource planning systems | | ■ | ▒ | ▒ | ■ |
| | Product lifecycle management systems | ■ | ■ | | | ■ |
| | Forecasting | | ■ | ■ | ▒ | |
| | Project planning system | | ■ | ■ | ▒ | |
| P5 Echelon elimination | Defined roles and responsibilities in projects | | ■ | | | |
| | Handover review and testing | ▒ | ■ | | | |
| | Framework agreements | | | ■ | | |
| | Accreditation of suppliers | | | ■ | | |
| P6 Design for X | Design for manufacturing/service | ■ | | ▒ | ▒ | |
| | CAD/CAM | ■ | | | | |
| | Product templates | ■ | | | | ▒ |

The tactics explained In Table 6 are notably different from those identified in earlier work related to material flow best practices in the automotive sector to reduce uncertainty (e.g., Towill et al., 2002; Childerhouse and Towill, 2004). These previous studies emphasised the importance of exemplar best practice areas such as single piece flow, supply chain relationships, optimised inventory policies, demand volume stability and the rationalisation of product variants as tactics for uncertainty reduction (Childerhouse and Towill, 2004). Our study indicates a different emphasis, one that is much more aligned with ETO situations and contexts. For example, it is possible to see important influences from project management practices and processes (e.g., project planning and learning), innovation methodologies (e.g., agile methods) and design management (e.g., prototyping). These findings concur with the differentiating approaches to uncertainty reduction in non-ETO versus ETO environments. In non-ETO, there is a sequence of focusing efforts to the internal process first, then supply side, followed by demand, while at the same time making efforts to minimise uncertainty through production planning and control systems (Towill et al., 2002; Childerhouse and Towill, 2004). In contrast, Alfnes et al. (2021) found that, in ETO, where engineering and production are part of the same process, there is a need to prioritise those efforts in both process and project control before then embarking on demand-side uncertainty reduction and later supply side.

Table 9 shows the principles and tactics from Gosling et al. (2015), which specifically focus on the construction sector, and the findings from our shipbuilding study in terms of RTO tactics and ITO tactics. Although the principles remain clearly recognisable and applicable, the tactics identified by Gosling et al. (2015) from construction supply chains deviate to a certain extent from the tactics we have found in the Norwegian ETO shipbuilding equipment supply industry. Important

**Table 8**
Principles, tactics and uncertainties of ITO.

| Principles | ITO tactics | Uncertainty type | | | | |
|---|---|---|---|---|---|---|
| | | Specification | Supply chain relation management | Engineering lead time | Supplier lead times | Product structures |
| P1 Time compression | Predesign analysis | | | | | |
| | Agile methods | | | | | |
| P2 Control system | Centralised cross-disciplinary project team | | | | | |
| P3 Synchronisation | Risk-sharing contracts | | | | | |
| P4 Information transparency | Design integration events | | | | | |
| | Knowledge transfer between projects | | | | | |
| P5 Echelon elimination | Cross-disciplinary innovation events | | | | | |
| P6 Design for X | Early customer and supplier involvement | | | | | |
| | Prototyping | | | | | |
| | Computer-aided modelling and simulation | | | | | |

tactics in both industries are automation, modularity, project planning, early supplier involvement, design for manufacturing/assembly, CAD/CAM, KPI systems, supplier accreditation, framework agreements and standard procedures. The description is slightly different for some common tactics, for example, 'standard procedures' versus 'standard procedures and contracts' and 'web-based project planning' versus 'project planning systems', which are nuances reflecting the local differences and time span between the case samples. However, tactics related to a certain level of repetitiveness, such as component rationalisation, lead-time visibility, sharing demand information, visual control boards, supplier rationalisation, JIT deliveries and Kanban, were not found in our shipbuilding study.

The sectoral based application and more refined exploration through the two system types allow for some interesting observations and discussion points. Here, many tactics in the construction and shipbuilding RTO columns will be familiar to those in the operations and supply chain disciplines. Such tactics found in construction and now in shipbuilding are well-established, which may, for example, be observed in standard lists of good operations excellence practices (e.g., Shah and Ward, 2003). However, the tactics in the shipbuilding ITO column of Table 9 would be much more recognisable to scholars and practitioners in the project management or innovation topic areas (e.g., Davies et al., 2009). This suggests that, when applying the principles in ITO systems, interdisciplinary concepts and learning will be increasingly relevant.

Our study has a greater emphasis on engineering compared with Gosling et al. (2015). All products in Table 3 involve engineering activities. In the workshops, the managers were asked to identify uncertainty sources and tactics to mitigate them, both for engineering and production. This refinement of the method revealed more tactics to mitigate the uncertainty related to engineering. For RTO projects, product specification assistant systems, stage gate execution systems, product lifecycle management (PLM) systems, defined project roles and responsibilities and handover review and testing procedures are all additional tactics to mitigate uncertainty related to engineering. ITO projects are more engineering intensive, and the additional tactics listed in Table 9 for such innovative projects are all related to engineering.

Interestingly, a difference in how digital technologies are applied in the two studies can be seen. There is a time span of seven years between the studies, and there has been rapid digitalisation of the industry during this period. Even more importantly, Norwegian maritime suppliers are delivering equipment to technologically advanced ships with demanding design (Alfnes et al., 2021). These ships are classified by Willner et al. (2016) as complex ETO products because of extensive order-specific engineering activities. Therefore, the suppliers'

**Table 9**
A comparison of tactics for construction and shipbuilding.

| FORRIDGE PRINCIPLES | Construction Suppliers Tactics (Gosling et al., 2015) | Shipbuilding Suppliers – RTO Tactics | Shipbuilding Suppliers – Additional Tactics for ITO |
|---|---|---|---|
| P1<br>Time compression | Automation<br>Modular platforms<br>Component rationalisation | Automation<br>Modular platforms<br>Product specification assistant system<br>Component inventory<br>Subcontracting | Predesign analysis<br>Agile methods |
| P2<br>Control system | KPI systems<br>Consolidation centre<br>Visual control boards | KPIs systems<br>Sales & operations planning<br>Material requirement planning | Centralised interdisciplinary project team |
| P3 Synchronisation | JIT deliveries<br>Kanbans<br>Standard procedures | Stage gate execution model<br>Supply chain coordination meetings Standard contracts and procedures | Risk-sharing contracts |
| P4<br>Information transparency | Web-based project planning<br>Lead-time visibility<br>Sharing demand information | Project planning system<br>ERP systems<br>PLM systems<br>Forecasting | Design integration events<br>Knowledge transfer between projects |
| P5<br>Echelon elimination | Supplier rationalisation<br>Framework agreements<br>Accreditation of suppliers | Defined project roles and responsibilities<br>Handover review and testing<br>Framework agreements<br>Accreditation of suppliers | Cross-disciplinary innovation events |
| P6<br>Design for X | Early supplier involvement<br>Design for manufacture/assembly<br>CAD/CAM/BIM | Design for manufacturing/service<br>CAD/CAM<br>Product templates | Early customer and supplier involvement<br>Prototyping<br>Computer-aided engineering modelling and simulation |

technology maturity level is high, and digitalisation has been a priority in the Norwegian government's maritime strategy since 2016 (The Research Council of Norway, 2016).

When the two studies are compared in Table 9, our study has identified several additional tactics that utilise digital technologies when compared with Gosling et al. (2015). For time compression (P1), product specification assistant software and systems for predesign analysis are used to reduce design uncertainties and waiting times in interactions with customers. All suppliers have installed an enterprise resource planning (ERP) system. The ERP system enables integrated control (P2) and reduced planning uncertainty through functionalities for sales and operations planning and material requirement planning. Synchronisation (P3) is improved through a digital stage gate execution model that enables the flows of activities and interactions during the entire order fulfilment process. Information transparency (P4) is supported by ERP systems that integrate supply chain information and provide forecasting functionality and by PLM systems that integrates CAD/CAM files and design specifications (P5). DfX (P6) is supported by CAD and CAM systems. In addition, computer-aided engineering (CAE) modelling and simulation systems are used to test products at an early stage.

The findings make several refinements to the original principles and tactics. First, the replication study points towards the possibility that different tactics might be employed depending on the type of ETO system. We have used the RTO and ITO distinction to show that certain tactics, many of which may be observed in the innovation project management discipline, may be needed for systems with ITO characteristics. These differences are highlighted in Table 9. Hence, the implication is that practitioners may take a more nuanced approach to devising approaches for mitigating uncertainty. Second, the analysis indicates that, via a combination of principles and tactics, all the most common sources of systemic uncertainty in RTO and ITO systems can be in some way addressed or alleviated. Tables 7 and 8 show the different interlinkages. This demonstrates their applicability in ETO shipbuilding.

## 8. Conclusion

At the outset, the present paper has aimed to undertake a replication study to investigate the reproducibility, reliability and validity of the FORRIGDE construction-based ETO principles and tactics framework developed by Gosling et al. (2015) as a way to mitigate uncertainty and extend the framework to the shipbuilding sector. The conceptual replication undertaken has highlighted the reliability of the six overarching principles postulated by Gosling et al. (2015) that govern uncertainty mitigation in ETO supply chains. By extending the sample from the UK construction industry to the Norwegian shipbuilding sector, we can reproduce the original study's findings that there are several tactics categorised according to the FORRIGDE principles companies may adopt in uncertainty mitigation. Although some of the tactics identified in the present study are the same or similar to those originally recognised, others are additions. Hence, we extend the original set of tactics for each principle and have indicated the significance of different tactics for the different ITO and RTO types of ETO.

We may have confidence that the original principles framework has external validity, with the potential for generalisability for ETO beyond construction. The applicability of the framework to the Norwegian shipbuilding industry suggests that there is generalisability to other forms of manufacturing-oriented ETO sectors, such as aerospace, capital goods and defence. Replication studies in other sectors can test this proposition and may further extend the set of tactics. More empirical research is also needed to investigate how tactics can be adopted, configured and implemented for different ETO types and sectors.

Our research makes a methodological contribution by showing the application of a conceptual replication research design in an operations management context. Although replication studies are common in the physical and life sciences, they are more limited in the social sciences. Hence, we provide a method that other researchers in the operations management field can exploit to enhance opportunities for theory development and testing.

Even so, given that this is one of few examples of undertaking replication studies in operations management, there is an opportunity for other research to enhance our approach. For example, by considering alternative forms of replication, such as strict or partial replication approaches or different forms of data collection for different target sectors.

In summary, the present research has highlighted the generalisability of the six overarching principles that govern uncertainty mitigation in ETO supply chains. Also, the original set of tactics has been extended for each principle and has indicated the significance of the different tactics for the different ITO and RTO types of ETO. In addition, a methodological contribution has been made by showing the application of a conceptual replication research design in an operations management context. The approach may be exploited by other researchers in the operations management field for theory development and testing in conceptual replication research, as well as testing the principles and tactics beyond construction and shipbuilding. Practitioners may also adapt the approach to undertake a holistic and structured diagnosis of systemic uncertainties in their ETO supply chains and adopt practices to mitigate them.

## Declaration of competing interest

None.

## Data availability

The data that has been used is confidential.

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