



Exploring systemic factors creating uncertainty in complex engineer-to-order supply chains: Case studies from Norwegian shipbuilding first tier suppliers

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

ARTICLE INFO

Keywords:

Innovate
Uncertainty
Complexity
Redesign
Soft systems

ABSTRACT

While it is recognised that there are varying uncertainty characteristics between industry sectors, there is little uncertainty research directly related to engineer-to-order (ETO) systems. A novel method is developed to identify the factors contributing to uncertainty in shipbuilding first-tier suppliers that inhibit the effective and efficient delivery of ETO products. The empirical data set comes from case-specific workshops involving cross-disciplinary staff from engineering, production, purchasing, planning and sales. The protocol included presentations by the researchers and the company, tours of the shopfloor and interactive sessions. The latter used 'brown-paper' exercises to map customer penetration-point locations, identify where uncertainties occurred and evaluate their impact-likelihood. The customer penetration-point mapping identified two ETO types; redesign-to-order (RTO) and innovate-to-order (ITO). The major challenges faced by ITO systems are caused through failures in (a) properly understanding customer requirements and translating those to product specification, (b) providing capacity and capability in engineering design teams at both first- and second-tier suppliers, (c) managing interfaces from customer through to second-tier suppliers. Engineering processes in RTO systems have poor customer configuration protocols leading to complex, overengineered products without pre-existing bill of materials. Engineering and production processes at both first- and second-tier RTO suppliers have extended lead-times with poor capacity availability. A change programme is suggested to reduce uncertainty requiring primary consideration of process and control aspects before addressing demand-side and then supply-side changes. The findings are evaluated by independent interviews indicating that the method and tools adopted have validity, and that the findings are commensurate with wider industry expectations.

1. Introduction

The shipbuilding industry is competitive and globalized. Europe is one of the key actors in the global shipbuilding industry together with China, South Korea and Japan. European shipbuilding provides a minor share of the global shipbuilding tonnage but has an approximate market share of 13% of the world orderbook in terms of value (Steidl et al., 2018). To cope with the Asian countries' labour cost advantage, the European shipbuilding industry, adopting a specialization strategy, has focused on innovation and building complex, high-value ships (Gasparotti and Rusu, 2018).

Shipbuilding can be categorised as complex engineer-to-order (ETO)

supply chains (Willner et al., 2016a) that produce large, one-of-a-kind products with high-engineering complexity. Shipbuilding relies heavily on supplied inputs, as around 70–80% of the final output value of ship production is generated through the upstream supply chain (Gourdon and Steidl, 2019). The European supplies industry accounts for approximately 16% of the global market of machinery and equipment to ships (Daniel and Takagi, 2019), and are ensuring that advanced equipment, such as engines, generators, propellers, thrusters, automation, bridges, and electronics, can be assembled at the shipyards. Uncertainty is high compared to other industrial supply chains and inhibits performance (Sanderson and Cox, 2008). Many components of the ship, even standard products like electrical cables, are exposed to high levels

* 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).

<https://doi.org/10.1016/j.ijpe.2021.108211>

Received 12 June 2020; Received in revised form 1 June 2021; Accepted 18 June 2021

Available online 25 June 2021

0925-5273/© 2021 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

of uncertainty, impacting suppliers throughout the network. Hence, efficient coordination of the supply base is a critical issue for supply chain management in shipbuilding (Mello and Strandhagen, 2011).

Uncertainty in manufacturing systems more generally has long been recognised as a major barrier for achieving system performance goals (Parnaby, 1979). Uncertainty is often used synonymously with other terms, such as disruptions, events and, most notably, risk (Sanchis et al., 2020), although risk may be an outcome of uncertainty. If everything was certain and known then managers could plan and make decisions to easily avoid risk. Hence, uncertainty in supply chains may be defined as “situations in the supply chain in which the decision maker[s do not know definitely] what to decide as [they are] indistinct about the objectives; lack information about or understanding of the supply chain system or its environment; lack information processing capabilities; [are] unable to accurately predict the impact of possible control actions on supply chain behaviour; or, lack effective control actions” (Van der Vorst and Beulens, 2002).

A model to rationalise and categorise uncertainty in a manufacturing systems context is the ‘uncertainty circle’, which conceptualizes the different sources that affect supply chain performance (Mason-Jones and Towill, 1998). The ‘uncertainty circle’ concept has been exploited and extended in wide range of different contexts, from automotive through to the construction sector, but not, as yet, the shipbuilding industry. For instance, Gosling et al. (2013) consider the ‘uncertainty circle’ in an ETO construction environment, proposing a method for identifying and categorizing uncertainties and linking them to project risk profiles. But Gosling et al. (2013) do not differentiate between engineering and production activities, and they do not propose an approach for reducing or managing uncertainties, and do not consider the complex interplay between uncertainties or value streams, which is evident in complex shipbuilding (Mello et al., 2017).

To understand the systemic nature of a problem as well as to deal with the dynamic nature of systems, wherein behaviours are always in flux, the soft systems methodology (SSM), espoused by Checkland (1999), provides a means to model causal relationships. The application of SSM is particularly pertinent to the design and production of ships due to the complex and ‘messy’ interactions found between people, technologies and processes (Mello et al., 2017; Williams, 2017; Aramo-Immonen and Vanharanta, 2009). However, it is not clear how soft systems tools and techniques interface with the aforementioned uncertainty circle framework to support decision making across shipbuilding supply chains.

The research focuses on the need to develop a more systemic approach to supply chain uncertainty within the particular context of ETO systems. Hence, the aim is to develop a method to guide companies in identifying systemic contributing factors for the occurrence of uncertainty in shipbuilding related first-tier suppliers that inhibit the effective and efficient delivery of ETO systems and to ascertain the pathway to change to reduce uncertainties. The empirical work, which exploits an SSM approach, is undertaken with the Norwegian shipbuilding supplies industry, one of the world’s leading providers of shipbuilding equipment, such as mechanical equipment and electronics (Helseth et al., 2018), and where there is typically a high amount of new complex engineering work to be undertaken for each customer.

The contributions of the study are to.

- 1) extend the existing material flow uncertainty circle identification approaches by explicitly considering engineering activities,
- 2) adopt the soft systems systemigram technique to get better visibility of uncertainties throughout an ETO system,
- 3) identify two new forms of ETO that have their own characteristics and challenges, and
- 4) reorient the uncertainty reduction change management pathway to account for engineering as well as production activities.

The structure of the paper is as follows. The next section explores the

literature on ETO systems, the ‘uncertainty circle’ and shipbuilding, highlighting the existing gaps in research. Then Section 3 gives a comprehensive account of the research design, including workshops and interviews, leading to the results in Section 4. The discussion in Section 5 reflects on contributions vis-a-vis the existing body of knowledge. The paper finishes with conclusions indicating the implications of the research for theory and practice.

2. Theoretical background

2.1. Engineer-to-order supply chains

To make strategic choices about a production system, it is helpful to consider the underlying structures, known as the customer order decoupling point concept, to identify an approach for dealing with the flow that activates deliveries to the customer. There are a range of potential production decoupling points, including buy-to-order, assemble-to-order, make-to-stock (MTS) and ship-to-stock, each having competitive trade-offs (Olhager, 2003). As one moves towards the ship-to-stock structure, lead times are reduced, but there is very limited scope for individual customisation.

ETO situations occur when a customer order penetrates deep into production processes, and then into design/engineering processes (Gosling and Naim, 2009). This idea has been further expanded to show a continuum of potential penetration points within the engineering process (Gosling et al., 2017). More specifically, Gosling et al. (2017) explain scenarios where engineering designs are developed to-order from positions of research and development (i.e. science or engineering testing), codes and standards (i.e. new designs from basic requirements and specifications), and finally, solutions developed from existing designs (e.g. in product libraries and existing drawings).

Building on Wikner and Rudberg (2005), Cannas et al. (2019), based on empirical work in the machine tools sector, argue for a 2-dimensional approach, which classifies decoupling positions across both engineering and production dimensions. This results in a series of potential configurations for different product families, balancing the aforementioned trade-offs with the type of market requirement.

In ‘pure ETO’ situations, or when the customer penetrates deep into engineering processes, for instance if orders are developed from research and development or codes and standards, innovative new design ideas will need to be developed to form a solution (Gosling et al., 2017). As the customer drifts further towards existing designs, then it is possible to enter the domain of *redesigning* products. Here, it may be possible to use existing product libraries, knowledge about product hierarchy and the bill of materials, to modify or adapt existing design (Amaro et al., 1999; Wikner and Rudberg, 2005; Gosling et al., 2017). If volume production allows, then it is possible to create pre-defined options to configure (Willner et al., 2016b; Cannas et al., 2019) or assemble a product to customer requirements (Song and Zipkin, 2003). In configure- or assemble-to-order situations, it may be possible to automate the design stages via maturity of processes, systems, people and strategy (Jiao and Helander, 2006; Willner et al., 2016b).

2.2. Uncertainty research

In situations where there is significant uncertainty, it is typically accompanied by behavioural issues such as over-reactions, unnecessary interventions, second guessing and irrational decision making (Childerhouse and Towill, 2004). The ‘uncertainty circle’ proposes four categories of uncertainty, including process uncertainties (in-house activities), supply (from suppliers), demand (from customers) and control (resulting from the planning and control of all activities). It is possible to observe a ‘flywheel’ effect, whereby uncertainty is amplified through the interactions between these different sources (Mason-Jones and Towill, 1998; Childerhouse and Towill, 2004) yielding vicious reinforcing loops (Williams, 2017).

Christopher and Peck (2004) determined that the various sources of uncertainty may be reclassified, and extended, as those internal to an organisation (process and control), those external to an organisation but within the same supply network (supply and demand), and a fifth category that is external even to the supply network. Such a categorisation allows individual companies and their supply chains to determine focussed resilience development strategies to mitigate against the risks of disturbances or detrimental events. Sanchez Rodrigues et al. (2008) reconceptualised the ‘uncertainty circle’ model to translate it from a dyadic customer-supplier perspective to consider the logistics triad, offering a more refined approach to prioritise uncertainty mitigation strategies that explicitly includes transport operations.

Building on earlier work of Stevens (1989), who proposed a stepwise approach to achieving integration across supply chains, the proposed pathway to manage uncertainty is to, first, address in-house processes, then the supply side, then demand and control jointly, incrementally learning from the different steps and reducing uncertainty associated with different areas of the uncertainty circle (Mason-Jones and Towill, 1998; Childerhouse and Towill, 2004). Evidence from applications of the framework supports this sequential supply chain reengineering approach to shrink uncertainty, suggesting a range of performance improvements can be achieved (Childerhouse and Towill, 2002, 2011).

Much of the research in supply chain uncertainty, and particularly in the sequential construct for uncertainty reduction, has been undertaken in non-ETO environments, in manufacturing sectors such as automotive and food (Towill et al., 2002; Aitken et al., 2016). Typically, they focus on production material flow and do not consider, at least explicitly, uncertainties generated or linked with the engineering processes. Hence, there has been some debate as to the extent to which the ‘uncertainty circle’ is relevant for ETO supply chains, where customised products involving new or unique engineering work is undertaken for a customer order often delivered as a one-of-a-kind/first-of-a-kind project. Even Gosling et al. (2013), when considering uncertainty in ETO construction projects, do not differentiate between engineering and production activities. It is important to distinguish between those uncertainties resulting from engineering and production as, when considered in combination, they define the positioning of the customer order penetration point (Wikner and Rudberg, 2005; Gosling et al., 2017; Cannas et al., 2019) as opposed to merely the traditional material flow perspective (Hoekstra and Romme, 1992). The positioning of the customer order penetration point then defines the type of ETO system in terms of the degree of uncertainty to be encountered and managed (Gosling et al., 2017).

Engineering projects are particularly susceptible to uncertainty given their innovative and complex nature with many interacting parts, including people, technology, materials and processes. Hence, the uncertainties generated are likely to be systemic, meaning that they are interrelated, rather than isolated occurrences (Williams, 2017). When mitigating against such uncertainties in ETO type systems, there has to be due consideration of the change management approach due to the interrelated nature of the sources of uncertainties such that prioritizing and phasing actions becomes a challenge (Gosling et al., 2013). Merely targeting specific actions may paradoxically have detrimental effects on system wide performance (Treville et al., 2004; Owen and Huang, 2007). A long sequence of change initiatives may protract the change programme and lead to burnout, but large scale system wide simultaneous change has considerable resource implications and can be overwhelming (Hammer, 2004).

2.3. Uncertainty in ETO shipbuilding supply chains

Shipbuilding projects are undertaken in a cyclical market. Ship demand increases during economic growth and drops during the recession (Steidl et al., 2018). It is challenging to achieve an effective ETO delivery process under such demand patterns. Semini et al. (2014) studied market interaction strategies for customized, low-volume shipbuilding,

and found that to move the customer decoupling point downstream towards more standardized design and predefined options might reduce uncertainty but also limit market opportunities. Dixit et al. (2019) investigate the value of customer involvement in ETO shipbuilding projects in India and found that lower customer involvement in the early stages and higher involvement during execution will have a detrimental effect on project performance. Strandhagen et al. (2020) investigated the sustainability challenges in shipbuilding supply chains, and propose digital solutions that, in order to effectively support sustainable operations, are tailored to the ETO approach in shipbuilding. Engineering changes (EC) leads to continuous adjustments in engineering, procurement and execution. Iakymenko et al. (2020) identified factors affecting the implementation performance of engineering changes in technologically complex ETO shipbuilding projects, and recommended EC management practices and tools to reduce the negative impacts of the identified factors.

Even though ships are built at a yard, shipbuilding has some similarities with large construction projects. The ETO delivery process is carried out by a multiorganization that involves, to a large extent, temporary actors to make one-of-a-kind products with frequent regulatory interventions (Emblemsvåg, 2014). A major complicating difference is that complex ships are technologically advanced products with a demanding design. Willner et al. (2016a) classified ships as complex ETO products because they require a high-engineering effort, are developed together with the customer from rough product concepts and have long lead times due to extensive order-specific engineering activities. Ships are mainly sold on the basis of product concepts that define main dimensions, layout, main space reservations, main equipment, and preliminary hull form. The largest part of design are done after the contract has been signed (Semini et al., 2014). Most ships, except the simplest and most standardized ones, are put into production and engineering before all engineering issues are solved to reduce delivery time (Emblemsvåg, 2014).

Literature explicitly focusing on uncertainty in shipbuilding supply chains is scarce. Mello et al. (2015) emphasized the complex interaction between actors in the interface between production and engineering, and suggested that overlapping project activities can make coordination of engineering and production very difficult, especially for large complex ships where customer changes are common. Vaagen et al. (2017) developed a stochastic model to understand the role of design uncertainty for project planning at the yard. They focused on strategic components where size, technical specifications, or even choice of supplier, might be changed late in the process by the customer, and demonstrated that to perform design and execution activities concurrently might be costly. Suppliers provide numerous components to the ship that will vary in complexity. The design of ETO-component can start by only knowing its footprint in the ship, and the supplier provides an increasing amount of technical documentation that are finalized before the outfitting of the ship starts. Emblemsvåg (2014) terms these “project components” to denote equipment that are developed during the project, and to differentiate them from “articles” that are predefined and just procured. The focus on first-tier suppliers has not been explored in previous studies. An exception is Sanderson and Cox (2008) that studies supply chains serving a major UK shipyard, and suggest that uncertainty is high compared to other industrial supply chains and inhibits performance.

Given the foregoing literature, we have shown that ETO shipbuilding projects has uncertainties and interrelated activities that affect and are generated by first tier suppliers. The uncertainty circle is a promising approach for classifying and managing uncertainty in ETO supply chains. However, the current approach is too focused on material flows and does not explicitly consider engineering activities. Further, it lacks the means to visualize how uncertainties are interrelated. A soft systems approach, exploiting visualisation tools, can be a supportive technique to map and visualize uncertainties in an ETO environment. Also, the classification of decoupling positions across engineering and production

dimensions is useful for investigating ETO supply chains. However, there is still a potential to exploiting such an approach in conjunction with ‘uncertainty circle’ analysis and mitigation to tailor a change programme to the attributes of different ETO types.

3. Method

3.1. Research design and phases

The critical realism paradigmatic lens espoused by Gosling et al. (2013) in their research on uncertainty in construction ETO projects is adopted. Similarly, but in a shipbuilding industry ETO context, the research endeavours to unpick the various aspects of reality to create descriptive models of generative system structures that help to define the various underlying mechanisms that lead to certain behaviours. Since the problem situation and context is relatively unstructured and ‘messy’ (as noted by Mello et al., 2017; Aramo Immonen and Vanharanta, 2009), the researchers adopted and integrated many tools and techniques from systems thinking to develop the descriptive models. To give structure and transparency for the overall method, the approach was broken down into a number of phases, each building on well-established (but until now not integrated) lines of research. While the approaches are well established, they have not before been integrated and synthesised into the pathway developed in this paper. Fig. 1 gives an overview of the methods used, and the phases of the research process.

Phase 1 focuses on classifying the underlying structures for different products, Phase 2 emphasises the identification and categorisation of uncertainties, and Phase 3 addresses a systems-based analysis. Phase 4 focused on evaluating and finalizing the descriptive models through validation interviews. There are two primary data collection activities: four multi-participant workshops to generate data for Phases 1–3, and six interviews for Phase 4. In total, inputs are gathered from 23 practitioners across the workshops, and 6 senior practitioners during the interviews. Each phase is founded on well-established traditions and methods, as shown from the theory informing each phase, but the

approach is innovative in the way that the various approaches are integrated. The integration of these approaches allows for a much richer understanding about the nature of ETO system uncertainty, as well as holistic insights, than would be possible by focusing on the individual phases of the research design.

The empirical data was collected based on a well-established protocol for data collection in exploratory research studies related to supply chain management (Evans and Jukes, 2000; Hong-Minh et al., 2001) and uncertainty (Rodrigues et al., 2010a; Gosling et al., 2013). This involved equipment supplier workshops and follow up discussions, by telephone and email, with the companies to control and clarify the information given in the workshops. Full details are given later in this section. The workshops are perception based, but with appropriate facilitation they can capture participants’ expertise and develop a consensus to the issue being addressed without causing too much disruption by taking up individuals’ time away from their routine duties (Hong-Minh et al., 2001).

Each workshop involved cross-disciplinary staff from engineering, production, purchasing, planning and sales. Companies were selected based on the likelihood of the companies engaging in ETO type products and projects, innovative engineering work and non-MTS production models. They also needed to be prepared to engage in resource intensive workshops, company tours, and open to meaningful debate with researchers about the nature of ETO systems.

The protocol involved a presentation by the researchers of previous ETO research and the purpose of the workshop, a presentation by a senior manager giving an overview of the company and its products, a tour of the shopfloor to highlight physical and information processes, and a facilitated interactive session. The interactive sessions (workshops) were undertaken in Norway during a period of four separate sequential days. The same four researchers were involved in facilitating the workshops and note taking. Two of the companies allowed recording of the workshops which was subsequently transcribed, while detailed notes from the other workshops document the data. Participants undertook a range of activities using visual displays on ‘brown paper’. As can be seen in Fig. 1, as per the key, the overall research activities cycle between those led by practitioners and others led by the researchers. This is consistent

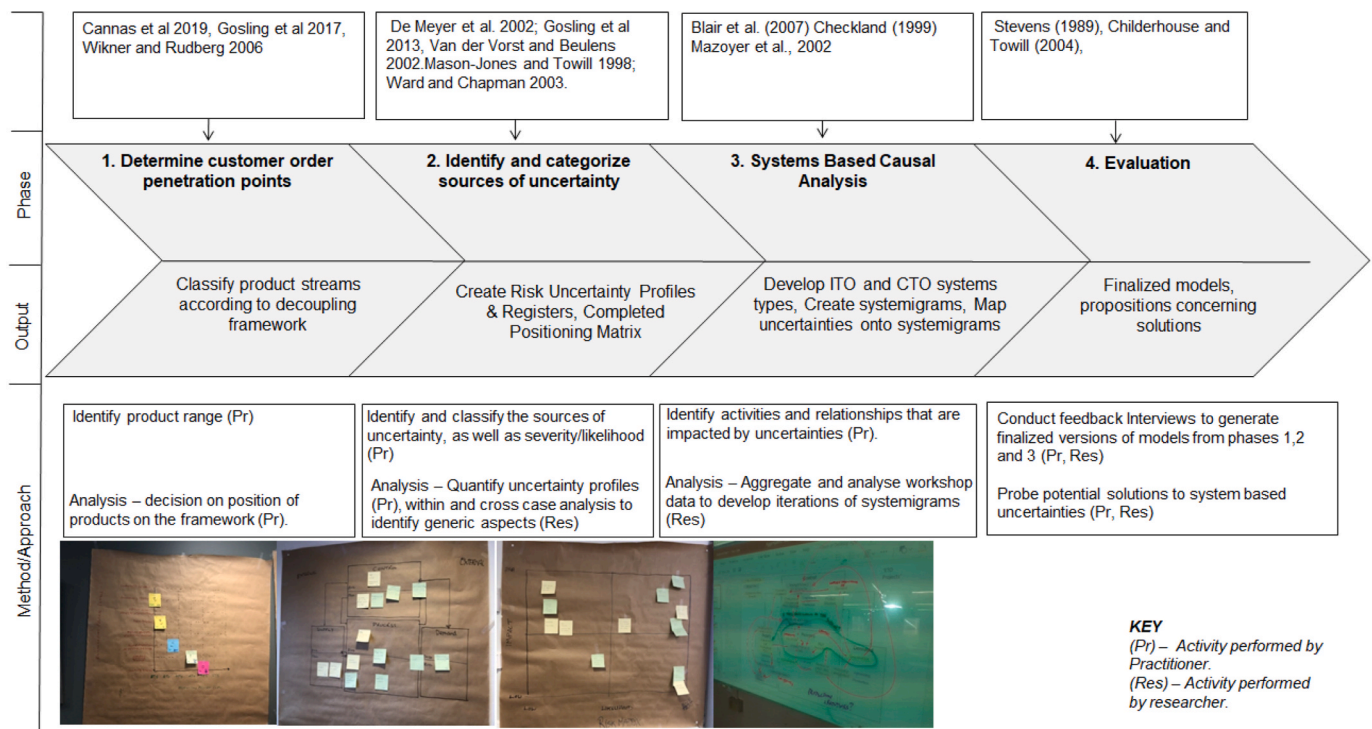


Fig. 1. Phases of the study.

with immersive, engaged research, and allows for the emergence of new insights and findings.

Phase 1 - At the outset of each workshop, which constituted Stage 1 of the workshop, participants established customer order penetration locations for both production and engineering value streams. This was undertaken by building on a line of research starting with Wikner and Rudberg (2005), who established the theoretical underpinning for different logistics structures, and then Cannas et al. (2019) who investigated the categories empirically to shape more precise definitions. Collectively, these studies give categories and definitions for underlying structures by which to compare different system types. The location of products on the customer order penetration, based on Cannas et al. (2019), were used as a basis to determine any differences in participants' experience of the uncertainties and their sources for different types of engineering and production environments. As denoted in Fig. 1, the practitioner participants decided which specific products would merit comparison and contrasting. Following the initial presentation given by researchers, practitioners were encouraged to choose products that have significant ETO attributes. Hence, very few standard products were identified. The left side of Fig. 2 shows the attendees for each workshop, the protocol used, and the purpose.

Phase 2 - Following Phase 1, several of the products identified were selected for further analysis. The choice of products reflected the practitioner participants' knowledge from earlier projects, or those that were particularly insightful for the company or study. Participants were asked individually to complete 'post-its' with the type of uncertainty encountered and to categorise them according to the 'uncertainty circle' model (Mason-Jones and Towill, 1998). The use of 'post-its' for mapping and problem identification exercises is well documented in operations (e.g. Fundin et al., 2018) and supply chain management (e.g. Evans and Jukes, 2000; Hong-Minh et al., 2001; Fabbe-Costes et al., 2020). More specifically it is exploited in uncertainty identification (e.g. Rodrigues et al., 2010a; Rodrigues et al., 2010b; Gosling et al., 2013), as it allows for individuals to make a note of their responses in private before sharing more widely within the group. Hence, it provides an opportunity for equal voices and no one individual to dominate proceedings

(Rodrigues et al., 2010a), which may be the case with particularly dominating individuals and/or where there are people present at different levels of authority.

The approach used by Gosling et al. (2013) is extended by differentiating between uncertainty factors associated with engineering and those to do with production. Then there is a determination of the scale of the uncertainties in terms of the probability of occurrence and the degree of severity of the uncertainty when it happens. This is analogous to risk assessment allowing for evaluation of uncertainty scores and prioritizing focus of study. This was done by using the technique developed by Gosling et al. (2013) where a large two-dimension graph, impact versus likelihood, was placed on the wall and participants were asked to position 'post-its' representing the uncertainties previously identified onto it.

The two-dimension graph only had analogue, low to high, axes rather than discrete scales. As noted by Reips and Funke (2008), such an approach allows participants to make more precise placements and are not forced into positioning to a narrow score. Gosling et al. (2013) note that a discrete scoring scale results in participants clustering their 'post-it' notes around a central score while the analogue representation enables a wider range of positionings to be realised and a fuller, more nuanced discussion about their placement. Hence, as per Gosling et al. (2013), a 0-4 scale was applied post-workshop activity to enable quantitative analysis and determining an uncertainty score.

This phase relied, firstly, on a within case analysis, where the research team analysed the product streams and uncertainties for a particular company, developing company specific diagrams and case summaries, then, secondly, a cross case comparison, where the uncertainties were compared, contrasted and aggregated across the cases. The findings presented flow from the cross-case analysis, but the depth of understanding came from the initial within-case analysis.

Phase 3 - This phase involved holistic causal relationship and time phased analyses. A problem structuring technique was adopted to understand the system wide implications of the uncertainties. Problem structuring methods (PSMs) allow for an appreciation of the implications of ill-defined problems in highly uncertain environments where

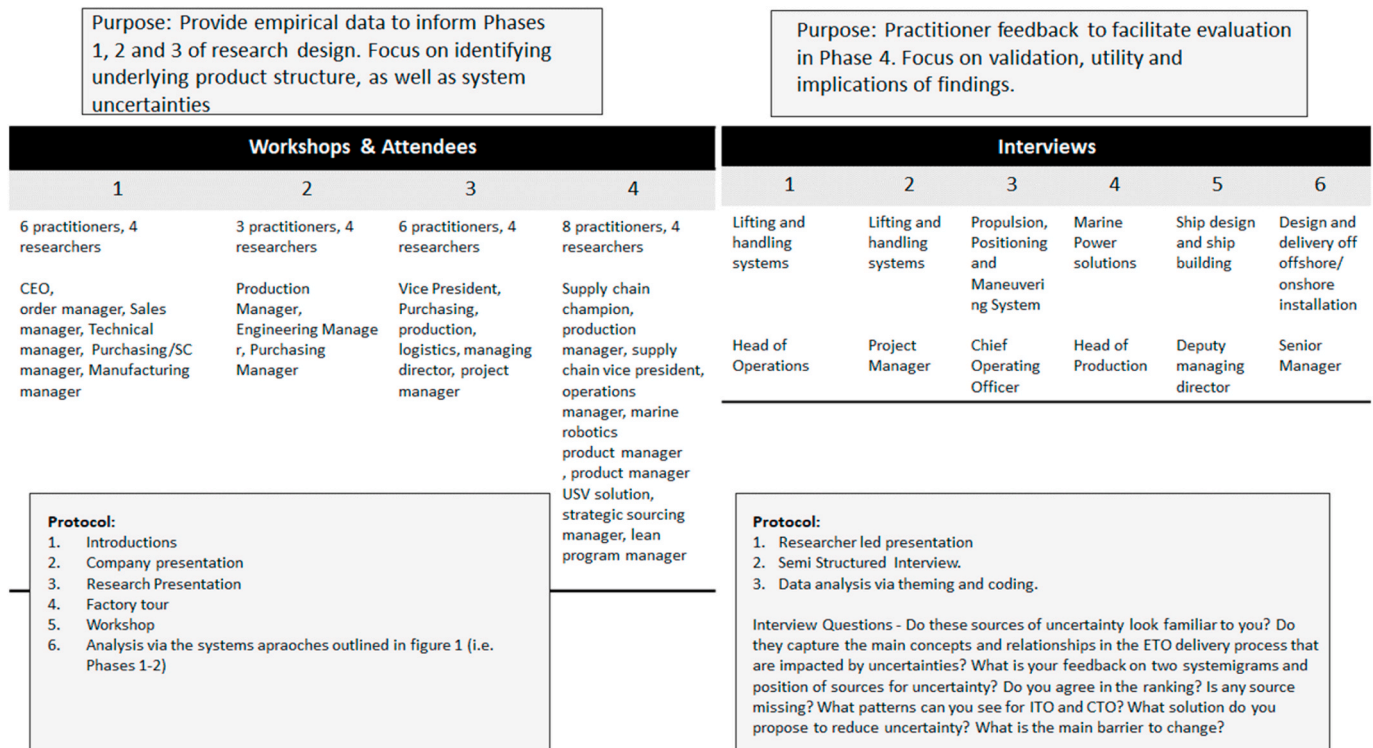


Fig. 2. Overview of data collection activities.

problems cannot be easily formulated using a positivistic approach (Mingers and Rosenhead, 2004). This is particularly pertinent in complex situations where cause and effect relationships are not easily discernible and are only obvious after events have occurred rather than being easily modelled and predictable (Kurtz and Snowden, 2003). Such an approach is in line with the SSM espoused by Checkland (1999), with a foundation in Vickers' (1965) appreciative systems theory, wherein complex systems are in continual flux and goal-seeking behaviours are a misnomer. Instead, companies seek to make sense of the situations that they find themselves in.

The systemigram PSM, proposed by Blair et al. (2007), was adopted and adapted to develop a descriptive model of the uncertainty conditions confronted by the four case companies. This allowed for a visualisation of the causal and temporal relationships between the uncertainties identified. In complex environments, narrative forms allow for a richer, more holistic, explanation of system behaviours leading to more refined management probing and sensing of events and resulting actions (Kurtz and Snowden, 2003). The systemigram concept allows for combining both prose and graphic thereby allowing for enhanced memory recall and retention (e.g. see Mazoyer et al., 2002). Systemigrams were developed based on the representations of Figs. 4 and 5 as well as the notes and transcripts recorded during the workshop.

Phase 4 - For this final phase, the research team synthesised data and insights from phases 1, 2 and 3 to develop a holistic representation of the system uncertainties. Six confirmatory interviews were undertaken at this point. The details for these are given in the right side of Fig. 2. The purpose was to gather feedback on the validity, utility and implications of the models developed, and the protocol and semi-structured questions asked are depicted in Fig. 2. First, interviews were transcribed to create detailed minutes of each interview. Then, they were themed and coded via highlights and colour codes. This allowed further synthesis of feedback to facilitate evaluation, including bullet point lists, question by question summaries, and organisation of feedback according to the phases of the research design. Key quotes were tabularised in line with emergent themes.

3.2. Overview of the organisations involved

The analytical aspects of the data collection were undertaken for several different products from each of the companies, as given in Table 1. The empirical data set comes from eleven products from the four companies. The companies were selected based on a purposeful sampling approach (Emmel, 2013). Given the shipbuilding context established at the outset of the paper, we focused on European companies with high level of innovation. First tier suppliers of complex shipbuilding systems, products and services in Norway were targeted, since such organisations are typical of niche specialist suppliers, and

Norway has almost 12% of the European share of the market (Daniel and Takagi, 2019). Based on Emmel's (2013) classification of purposeful sampling, we selected cases that offer, firstly, intensity of insight into risk and uncertainty in ETO situations, secondly, companies that are representative of the innovative shipbuilding sector, and thirdly, organisations that were willing to engage with a multi-disciplinary workshop approach and explore their own risk and uncertainty issues in a critical way. All four companies are suppliers operating in the premium segment of the shipbuilding and marine market. The products offered are within a range of different customer-initiated specifications, based on technology and brand as the main value adding and order winning criteria.

The products were self-selected by workshop participants, but picked in order to offer variation of theoretical dimensions, aligned with Emmel's (2013) maximum variation selection approach, in relation to the decoupling configurations (as per phase 1 of the research design). Two products are part of the portfolio of focal Company 1, three products from Company 2, two products from Company 3 and four products from Company 4.

Company 1 is a supplier of power systems for the offshore and maritime market. Customers are shipyards, rig-operators, vessel-operators and internal maritime customers. The workforce consists of 220 employees. Two of their main products, electric power systems and energy storage system, were selected for the study by the workshop participants. Both are mature, complex, and capital-intensive electronics products with established design templates and specifications. Each project requires 100–300 engineering hours to meet customer requirements.

Company 2 provides a wide range of sensor solutions to the global maritime industry. Customers are oil & gas operators, shipyards, ship owners and engineering companies. The workforce consists of 120 employees, and they are managing 50–60 different projects at the same time. Three products were selected by the workshop participants. The pressure transmitter is a standard MTS product and an important component in many of their ETO products. The wear monitoring system and the tank measurement system are both customised systems that are specially designed to provide continuous and reliable accuracy in the demanding environments. The tank system is based on innovative technologies and is still under development, so a significant amount of engineering, and the support from R&D, is required in each project.

Company 3 is a supplier of customised hydraulic and control systems. Their customers are mainly in offshore and maritime industry, but they also have customers in process industry and defence. The workforce consists of 100 employees, and they are managing more than 100 projects at the same time. Two products were selected by the workshop participants. Customised hydraulic cylinders are provided in a wide range of dimensions and features. Some engineering is required to customise cylinder brackets. The system for high precision during heavy

Table 1
Summary of company and product characteristics.

Product	Volume (quantity per year)	Duration (weeks)	Cost per unit (k€)	Engineering hours (hours per product)	Customer initiated engineering changes (# per year)
1 Energy storage system (Company A)	20–30	19-41 (28)	100-1000	100–150	0
2 Electric power system (Company A)	30	16-24 (20)	1001–10,000	350	30
3 Pressure transmitter (Company B)	8000–10,000	0.2–2 (1)	1–10	0	0
4 Wear monitoring system (Company B)	180–280	3-52 (4)	101–1000	10	0
5 Tank measuring system (Company B)	25–60	12-104 (56)	101–1000	500	10–15
6 Hydraulic cylinders (Company C)	20–30	3-8 (6)	1–10	0.5–2	0
7 High precision lifting system (Company C)	1	26-52 (32)	101–1000	100–200	0–5
8 Sonar marker (Company D)	60,000	(0.2)*	1–10	0	0
9 Unmanned Surface Vehicle (Company D)	20	40-60 (52)	1 001–10000	100	50
10 Autonomous underwater vehicle (Company D)	12	30-56 (40)	1001–10000	800	100
11 High resolution sonar (Company D)	24	16-26 (20)	101–1000	700	50–100

lifting and lowering operations is a complex and innovative product that requires substantial engineering and R&D in each project.

Company 4 is a global supplier of marine vessel robotics and underwater sensor systems. The company’s workforce is approximately 430 employees, and they provide a wide range of customised products. Four products that represent different levels of engineering effort were selected by the workshop participants. The sonar marker is a standard MTS product and crucial component in several ETO products. The unmanned surface vehicle is assembled from standard components, but some engineering is needed to meet customer requirements. The autonomous subsea vehicle and the high-resolution sonar are both innovative and complex products that require substantial engineering and close collaboration with R&D in each order.

Table 1 shows that the ETO products in the study are produced in small volumes. There were two exceptions, the sonar marker and the pressure emitter. These are MTS parts produced in thousands and used to build the ETO products. MTS products have been well studied in the literature and were not elaborated during the workshop activities.

4. Findings

This section presents the analysis according to the phases of the study illustrated in Fig. 1.

4.1. Determine engineering and production decoupling configurations

In the first phase, participants in each workshop mapped production and engineering decoupling configurations for their product families (identified in Table 1) onto the framework in Fig. 3 in order to compare different system types. It shows the interaction of production and engineering flows, and the penetration of the customer orders within each.

The analysis of the engineering and production decoupling choices shows that companies were able to plot products/projects across the range of different possible configurations. They perform some research and development projects, but the main volumes are ETO products with minor adaptations. It can be seen that for some cases the customer is closely involved in the whole process from idea to commissioning. The

projects are either initiated by a customer’s needs (no. 7 High precision lifting system), or initiated by a market opportunity for a family of products and initial research and development activities are done to forecast (cases no. 5 Tank Measure, 10 Autonomous underwater vehicle, 11 Sonar). The production processes performed to order range from “pure” ETO-production where most elements in the product structure are designed for a particular product, to more hybrid MTO/ATO production processes (no. 1 Energy storage system, no. 4 Wear monitoring system, no. 9 Unmanned surface vehicle) where only a smaller share of the components involve engineering.

As well as the classic MTS, two novel system archetypes emerged during this stage of the analysis: innovate-to-order (ITO) and redesign-to-order (RTO) systems. ITO systems are concerned with the generation of innovative projects that have much in common with the research/codes and standards engineering classes identified by Gosling et al. (2017). Research and development are either initiated by a customer’s needs or by a market opportunity, but the majority of the research and development activities are done on contract. Components are designed, and then produced or purchased to order (cases no. 5, 7, 10, 11). RTO systems are primarily concerned with the production of products developed from existing designs. In this latter category, there is much more potential for configurators and the application of mass customisation concepts. The starting point for RTO systems are designs from earlier projects that are made available in the company catalogue. The designs are modified and applied to specific components, and these are then produced or purchased to order (cases no. 1, 2, 4, 6, 9).

The ITO and RTO systems have some unique characteristics that makes it natural to treat them as two different value streams even if they share many resources. ITO systems require hundreds of engineering hours and are performed in close collaboration with R&D personnel and technical specialists. The projects are altering state-of-the-art technology to develop unique and premium-priced solutions for the customer. RTO systems are executed with the minimum number of engineering hours that are required to exceed the fixed solution space of standard make-to-order products. The projects are competing in a price-sensitive market by offering slightly customized designs that provide exactly what the customer wants.

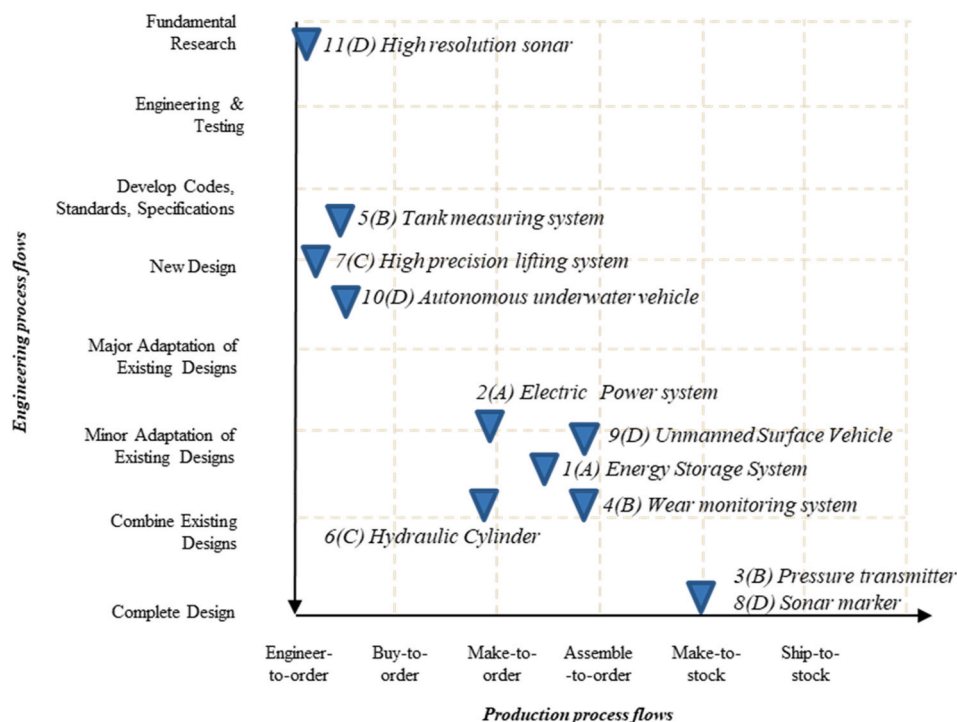


Fig. 3. Engineering and production decoupling configurations.

4.2. Identify and categorise sources of uncertainty

The second phase consist of three steps. Step one was for the workshop participants to identify uncertainty sources for each of their product families, and to categorise them according to the extended ‘uncertainty circle’ model enhanced from Mason-Jones and Towill (1998). The extended ‘uncertainty circle’ diagram consisted of the main categories process, control, demand, supply and external (the latter added from Christopher and Peck, 2004), and each main category is divided into the subcategories of engineering and production. The workshop participants confirmed that the new distinction between engineering and production was useful for their categorisation.

Step two was to identify the relative importance of different uncertainties. This was undertaken in the workshops by assessing the uncertainties for each product family in a severity/likelihood matrix. The third step was performed by the researchers. The uncertainties across all cases were grouped as either ITO or RTO types and represented in two summarising severity/likelihood diagrams. Figs. 4 and 5 present the severity/likelihood profile of all uncertainties for ITO and RTO respectively, and their categorisation as process, control, supply, demand, engineering, and production that were identified by the workshop participants in Phase 1. Tables 2 and 3 tabulate and enumerate the visualisations of Figs. 4 and 5, and collectively they give uncertainty profiles for different system types.

Fig. 4 provides a summary of the sources of supply chain uncertainty for ITO cases across the companies. 15 of the 18 uncertainty sources identified for ITO are ranked as high impact with only four of those having low likelihood of occurrence. Of the 18 uncertainties, four are categorised as control uncertainties, five are process related, with one each related to demand and supply. Another four belong to two categories with no distinguishable pattern evident. None of the uncertainties are categorised as external factors. Control uncertainties are related to specification of products, a high level of newness of the product structure, and lack of configuration rules. Such uncertainties in engineering also create waiting and delays in production. Process uncertainties are due to long lead times, R&D resources and knowledge in engineering. Demand uncertainties consist of multiple orders and bids that are competing for the same engineering resources, and the management of

relationships with customers and suppliers. Supplier’s development effort and lead times make up the supply category.

The uncertainties evident for RTO cases are given in Fig. 5. The majority of the 22 uncertainty sources identified, 16 in total, are ranked as high impact although six are of low likelihood. Of all the uncertainties, four are in the control category, four are process, one is due to supply, and six belong to two categories. None are categorised as either solely demand or of an external cause. Control uncertainties consist of unclear priorities and overengineering of products, lack of common rules and module interfaces, and the planning of production capacity and supply. In the process category there are uncertainties due to lead times and capacity in production. Within demand uncertainties are multiple orders and bids, and unclear product configurations. Finally, in the supply side there are uncertainties due to changing sub-suppliers and their delivery performance.

For comparative purposes, the detailed ranking and categorisation of the top 15 uncertainties for ITO and RTO systems are shown in Tables 2 and 3

Table 2 shows that the five most important uncertainties are specification, supplier lead times, relationship management, product structure and engineering lead times. These are mainly related to collaboration and coordination in the engineering supply chains from customer to sub-supplier. The majority of uncertainties are related to engineering. Such a profile may be explained by the degree of innovation required, consisting of unique solutions, lack order clarity, have unpredictable engineering requirements and require considerable production effort.

Table 3 shows that the five most important uncertainties for RTO systems are over engineering, configuration, lead times, lack of common rules and production capacity. The engineering process for RTO products is based on redesign and modification of existing designs and is more stable than for ITO products. RTO products compete on efficient operations, and particularly production since prices and margins are lower. The largest share of uncertainties is related to production.

ITO systems will typically involve more unknowns and experimentation, and hence one should expect more uncertainty. However, Tables 2 and 3 show that the aggregated likelihood and impact for uncertainties were lower in ITO than RTO systems. The main reason for

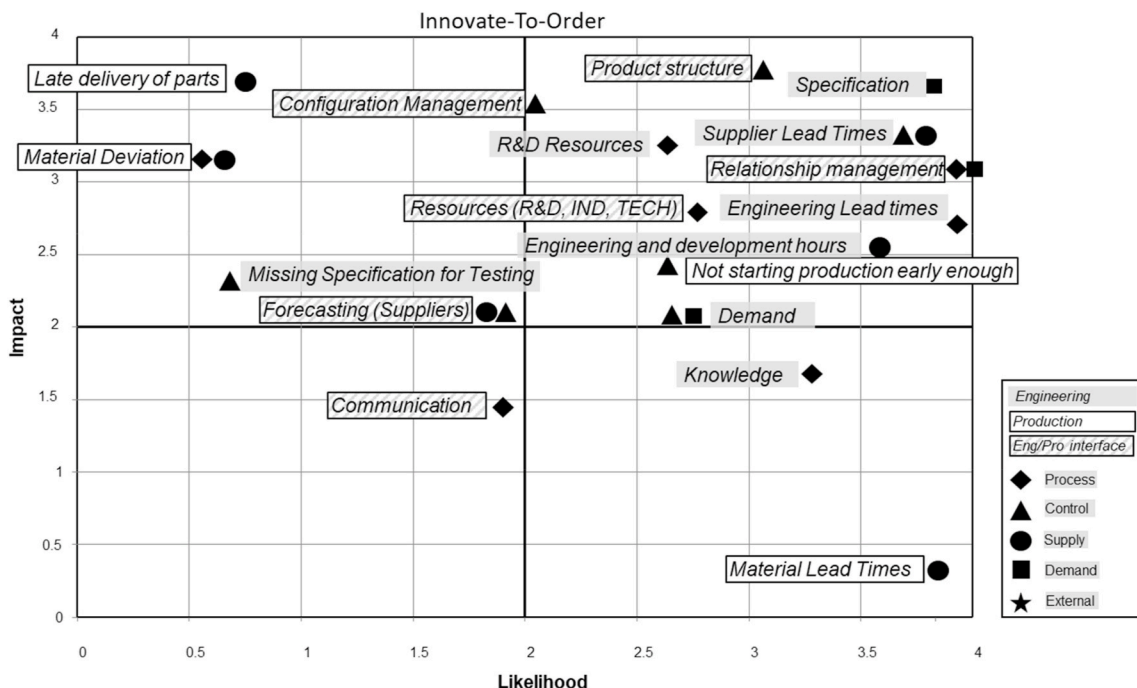


Fig. 4. Innovate-to-order systems positioning matrix for uncertainties (adapted from Gosling, 2011).



Fig. 5. Redesign-to-order systems positioning matrix for uncertainties (adapted from Gosling, 2011).

Table 2
Ranked Uncertainty Profile with Source Categorisation for ITO systems.

Uncertainties	#	Flows		Uncertainty sources				Severity		
		Engineering	Production	Demand	Process	Supply	Control	Likelihood	Impact	Likelihood X Impact
Specification	1	x		x				3,5	3,6	12,6
Supplier lead times	2	x				x	x	3,4	3,2	10,9
Relationship Management	3	x	x	x	x			3,7	2,9	10,6
Product Structure	4	x	x				x	2,8	3,6	10,1
Engineering Lead Times	5	x			x			3,6	2,8	9,8
R&D Resources	6	x			x			3,0	3,3	9,7
Configuration Management	7	x	x				x	2,4	3,6	8,6
Engineering and Development Hours	8	x				x		3,4	2,4	8,2
R&D Resources in production	9	x	x		x			2,8	2,7	7,3
Not starting production early enough	10		x				x	2,4	2,4	5,8
Demand	11	x		x			x	2,4	2,2	5,2
Knowledge	12	x			x			3,0	1,6	4,8
Forecasting (Suppliers)	13	x	x			x	x	1,6	2,2	3,5
Communication	14	x	x		x			1,7	1,4	2,3
Missing Specification for Testing	15	x					x	0,9	2,5	2,3
SUM:		14	7	3	6	3	7	40,4	40,3	111,5

this difference is that RTO products are made in higher volumes and with lower margins, so uncertainties occur more often and have a more severe effect on profitability.

Fig. 6, based on Tables 2 and 3, shows how the uncertainty sources are distributed between engineering, production and engineering/production interfaces.

Fig. 6 shows that ITO systems mainly have uncertainties in engineering, these create a ripple effect that disturbs production. Projects that involve innovation have good margins, and the main value creation are in specification and design. Projects that modify existing designs do not have the same margins and are competing on effective execution and streamlining of all activities in the supply chain. Fig. 6 shows that RTO systems mainly have uncertainties in production. However, uncertainties in engineering create delays and quality issues that adds to the uncertainties in production.

Based on the rankings of Tables 2 and 3, Fig. 7 shows the importance of uncertainty categories.

Looking at the likelihood/impact of uncertainties, and which activities are affected by the uncertainty, Fig. 7 illustrates that, for ITO systems, control and process are the ones with the highest score followed by demand and supply activities. For RTO systems, process, then control, demand and supply activities are the ranking. From a change perspective this indicates that the priority for managing uncertainty may be different for ITO and RTO systems.

4.3. System based causal analysis

A systemigram (Blair et al., 2007) was created to visualize the causal and temporal relationships between the uncertainties identified. They were developed based on the representations of Figs. 4 and 5 as well as the notes and transcripts recorded during the workshops. The systemigram representation was adapted to include the temporal stage from obtaining a customer request for a product though to its delivery. The three stages are;

Table 3
Ranked Uncertainty Profile with Source Categorisation for RTO systems.

Uncertainties	#	Flows		Uncertainty sources				Severity		
		Engineering	Production	Demand	Process	Supply	Control	Likelihood	Impact	Likelihood X Impact
Over engineering	1	x	x				x	3,7	3,8	13,9
Configuration	2	x		x	x			3,6	3,8	13,7
Lead Times	3		x		x			3,6	3,6	12,8
Lack of Common Rules	4		x				x	3,7	3,5	12,8
Production Capacity	5		x		x			3,6	3,3	11,7
Supplier On-Time Deliveries	6		x			x		3,0	3,6	10,8
Production Lead Times	7		x		x			3,2	3,2	9,9
Planning of Delivery Dates	8	x	x	x	x			3,7	2,4	8,9
Production of Parts	9		x				x	3,6	2,2	7,9
Complexity of Module Interfaces	10	x					x	2,6	3,0	7,7
Production Planning and Capacity	11		x	x			x	3,2	2,0	6,4
No Bill of Materials	12	x			x			3,6	1,5	5,4
Safety Stock	13		x	x			x	1,7	2,7	4,6
Resources and Time	14		x	x	x			1,7	2,4	4,0
Changing Sub Supplier	15	x				x	x	1,0	3,2	3,0
SUM:		6	11	5	7	2	7	45,5	44,2	133,5

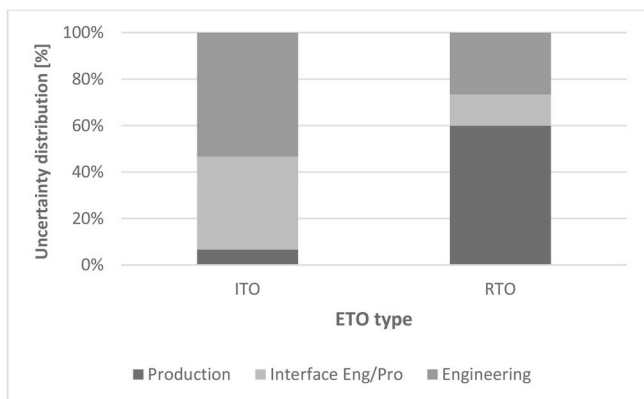


Fig. 6. Distribution of uncertainty sources in engineering and production.

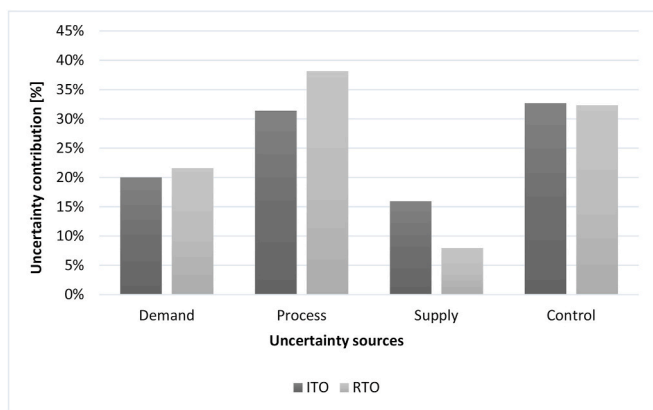


Fig. 7. Distribution of likelihood x impact per category.

1. Specification and design – wherein the clients’ needs are identified, the product specification is developed and a design established. Depending on the degree of customisation required this stage may entail new product innovation with one/first-of-a-kind design, development and adaptation of existing designs or exploitation of existing designs.
2. Mobilisation – during this stage the company ascertains its capabilities to determine a programme for the delivery of a project and

organises its human resources, physical assets and supply base to execute the delivery.

3. Production – materials flows including supply, manufacturing, assembly, testing and/or distribution of the final product.

While in all three stages there may also be an element of the delivery of services, here there is focus purely on the product itself as service elements did not emerge from the data collection phase. It was established that the supply base will be a sub-system of the system of interest and each supplier will undertake the same three stages of delivery with the focal companies as the customer. The systemigram was used to map the top uncertainty scores given in Tables 2 and 3 Figs. 8 and 9 show the systemigrams with uncertainty mapping for ITO and RTO systems.

A simple pattern matching indicates that the ITO systems has the main share of uncertainty sources related to collaboration in specification & design, i.e. how sales, engineers, R&D specialists at the supplier and sub-supplier collaborate to understand and fulfil the customers need. In contrast, RTO systems do have substantive uncertainties related to production. Uncertainties in planning and procurement within mobilisation, and resources and lead-times in the execution are affecting production performance. Supplier uncertainties are small or non-existing for both types, although there are interface issues with the supplier. Another key output of the systemigrams of Figs. 8 and 9 is that they indicate that the various uncertainty factors are not mutually exclusive, and hence they show their systemic impact throughout the ETO process from customer specification through to final product delivery.

4.4. Evaluation

Appendix 1 summarises the feedback obtained using quotes from the interviews undertaken. It is possible to see that, while there are some areas of critique and areas for further study for the method, the interviewees recognised the findings as valid and could relate to the issues presented. While there may be some context specific elements in each application of the method, for example the relative importance of uncertainties and types of uncertainties, the method is useful and insightful.

For Phase 1 of the research process, determining the customer order decoupling points, interviewees recognised the distinction between RTO and ITO, and were able to relate to the various decoupling configurations. As shown, for example, in I5: “Most projects have a high level of innovation (ITO), but we also deliver repeat projects (RTO)”. However, the innovation and redesign distinction, while useful, needs further explanation and clarification. In relation to Phase 2, identifying and categorizing the sources of uncertainty, interviewees recognised the

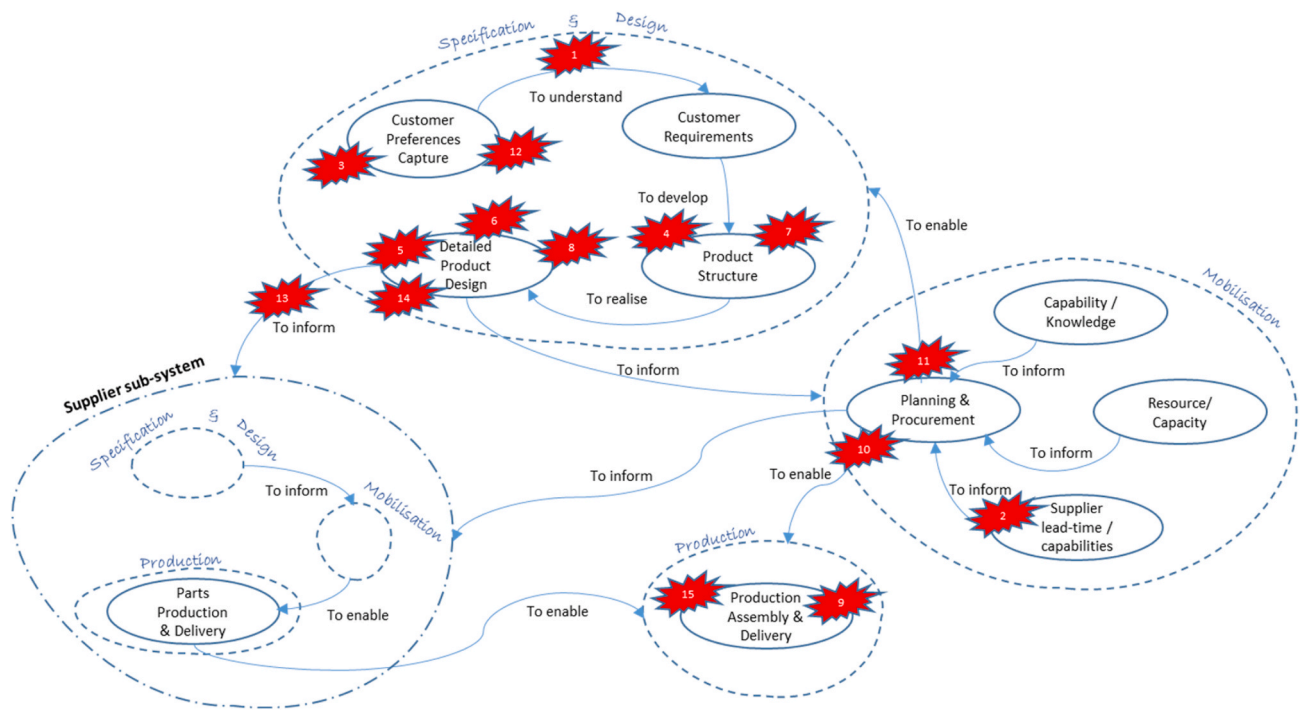


Fig. 8. ITO systemigram with uncertainty evaluations.

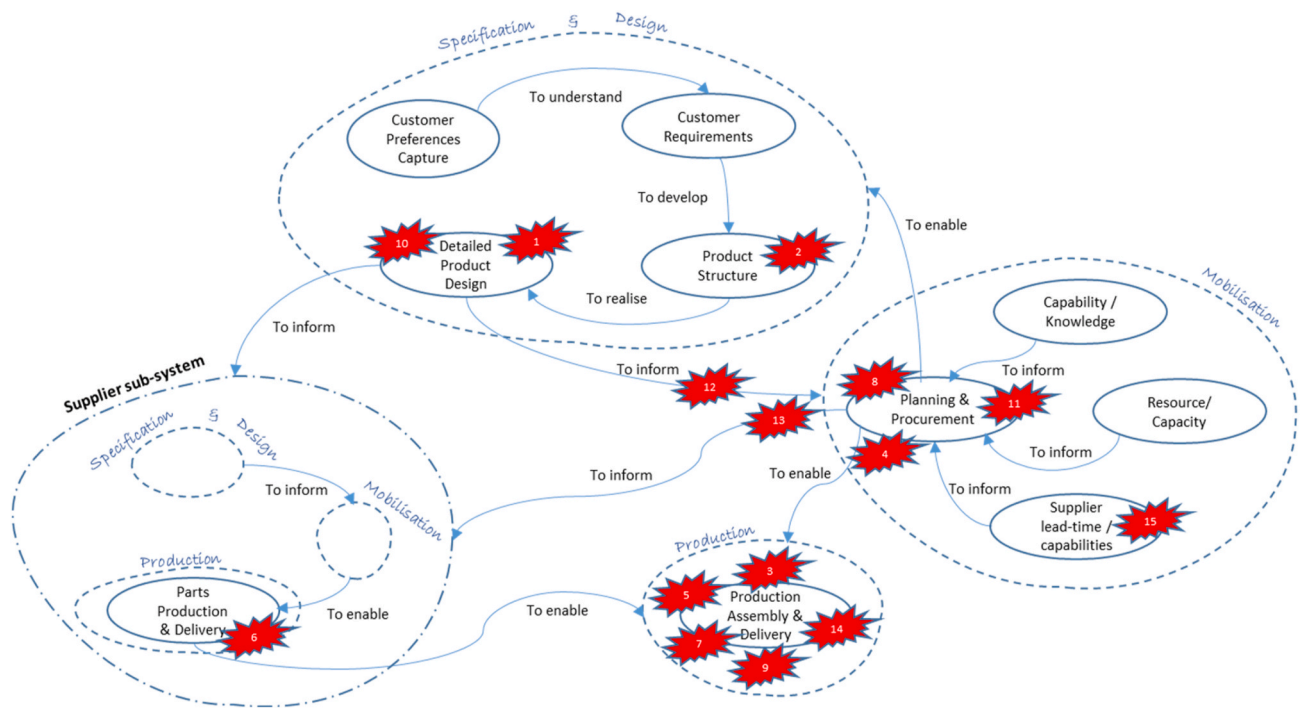


Fig. 9. RTO systemigram with uncertainty evaluations.

uncertainties for ITO and RTO systems but included further examples. Design changes and the level of concurrency in design and production were highlighted as areas that were not identified in the workshops. For example, in I4: “I recognize these sources of uncertainty, but where is design changes?” The lack of external factors was noted. For example, in I5: “Where is market, facilities and assets, organisation, and economy? All the factors will depend on these conditions”. The interviewees also provided more elaborate descriptions of the top sources of uncertainty. The top five sources identified for ITO systems are described in Table 4.

RTO systems consist, per definition, of a lower level of customisation and engineering work than the ITO system. The top five uncertainties identified for RTO systems are described in Table 5.

For the final phase, the system based causal analysis, the systemigrams were found to be a useful visualisation for showing the system perspective, and for prompting discussion between different members of the supply chain. In addition, it has utility as a ‘mind map’. An important pattern that emerges from the interview feedback is the impact of uncertainty generated from the sales and design process, as commented by

Table 4
Description of top five uncertainties for ITO.

Uncertainty source	Description based on interviews (see Appendix 2)
1. Specification	The high level of innovation, customisation and complexity of these products make it difficult to capture all customer requirements, and to understand all technical challenges that follows with a contract. The fulfilment process starts with a very aggregated and open specification which is detailed during the fulfilment process in dialogue with the customer. Such an iterative specification process generates changes that need to be handled efficiently.
2. Supplier lead times	Contracts are often agreed specifying shorter delivery times than the actual lead time, i.e. what it takes to engineer, source and produce the product, mainly caused by the lack of order clarity and detailed specifications.
3. Relationship management	Communication is not sufficiently intensive and rich, and inclusive regarding competence/skills to build common knowledge and establish mutual understanding between actors in the supply chain about the product under development.
4. Product structure	For one-off products, a large spectrum of potential functionalities, and rapid technology development require that unique product structures are designed for each order. Engineering must simultaneously handle a multitude of unique product structures without clear configuration rules.
5. Engineering lead times	Engineering works simultaneously on multiple projects. Each project involves disciplines such as mechanical, electrical and hydraulic engineering, and also external stakeholders such as customers and suppliers. The iterative nature and many handovers between different actors are time consuming and create long queues/waiting times in the engineering process.

Table 5
Description of top five uncertainties for RTO.

Uncertainty source	Description based on interviews (see Appendix 3)
1. Over engineering	Engineering tends to design RTO products to be more robust or advanced than necessary for their application. Hence, issues arise from over-specification the offering to customers, and a 'customisation creep' through interactions between customers, sales and other internal departments.
2. Configuration	Engineering processes in RTO systems have poor customer configuration protocols and are lacking detailed configuration rules, pre-existing bill of material and predefined modules which make the engineering of products to work intensive and slow.
3. Lead times in production	Production is set up a high level of flexibility, and not for efficient flow and short lead times. Production processes at both first- and second-tier RTO suppliers have extended lead-times with poor capacity availability.
4. Lack of common rules.	The lack of predefined modules and configuration rules makes engineering of products too work intensive and slow, and allow designs that creates problems for production and testing.
5. Production Capacity	The market is characterized by fluctuations in demand that are hard to predict. Capacity planning is difficult, especially regarding human resources. The cause for long delivery times in peak periods is the lack of skilled workers in production.

one of the interviewees *"Everything depends on sales. When there is uncertainty from the beginning, everything becomes uncertain"* (I1). Areas highlighted for further work or research include a better distinction between conceptual design and detailed design, as well as the sales link. Supplier relationships may also be under emphasized in the current models.

5. Discussion

The phenomenon explored by the method developed for this study is an extension of the research design of Gosling et al. (2013) who

identified the uncertainties in a construction ETO environment, with specific reference to 'one-of-a-kind' configuration. In their approach they exploited the 'uncertainty circle' concept (Mason-Jones and Towill, 1998), to ascertain and categorise uncertainties into the four sources, and undertook a risk evaluation of those uncertainties. To contend with the different operational environments found in the shipbuilding sector, where there is more likelihood to find varying operational and supply chain conditions, such as 'first-of-a-kind' and repetitive engineering and manufacture, the research has extended and enhanced the Gosling et al. (2013) approach by:

1. Adding an additional data collection step at the outset. The two-dimensional engineering-production decoupling framework of Cannas et al. (2019) was adapted to determine different operating system types. The following stages in the data collection are then differentiated according to the system types identified.
2. Enhancing the uncertainty circle model by giving due consideration of both engineering and production activities.
3. Additional analysis to understand the systemic factors of uncertainty through the application of systemigram modelling, which allows for due consideration and illustration of the system wide implications of the uncertainties identified.

The novel approach allowed for the identification of two new ETO types, ITO and RTO, each with its own operational characteristics and uncertainty profiles. The term RTO has been used twice previously by Arafati (2017), defined as "the re-use of past projects to satisfy customers' requirements" and Horna (2018), who specifies it as "Research and development are performed before the order issuing". The definition adopted here is congruent with the well-established spectrum of ETO types (Amaro et al., 1999; Wikner and Rudberg, 2005; Gosling et al., 2017). ITO has much in common with the underlying features of the 'research' ETO type identified by Gosling et al. (2017). The method allows for a more finessed technique to understanding their attributes and behaviours, their coexistence and implications on uncertainty.

A fundamental issue that arises, from both the discussions at the workshops and subsequent interviews, is that the ITO and RTO types in all the organisations exist in the same value stream, sharing the same people and resources in both engineering and production. When capacity is restricted, such as with too few specialist engineers, combining the two systems in one value stream may be the cause of additional uncertainty. While the systemigrams indicate unique locations of uncertainties for the different systems, merging them together would indicate that the whole system has great potential for systemic failure. And the suggested phases for uncertainty reduction only have credibility if the two systems are distinguishable.

There is a need for all organisation to consider the viability of separating the two systems into different processes because it might impact on flexibility and capacity, especially in engineering. As the interviews identified, and as corroborated by previous research (Jiao and Helander, 2006; Willner et al., 2016b), the inherent skills required by the people undertaking engineering tasks are very different for ITO and RTO environments.

The research method allows for better consideration of change management. The traditional approaches, especially with respect to supply chain integration (Stevens, 1989) and uncertainty reduction (Mason-Jones and Towill, 1998; Childerhouse and Towill, 2004), have focussed on material flows, or production activities. By additionally considering the engineering aspect of an operation it is possible to better determine the varying priority areas to focus management (people, organisation, technology and finance) effort and to distinguish between different operational environments. Hence, it is found that the pathway of change for the ITO and RTO types are different than the traditional material flow perspective.

The relative importance of the different uncertainty sources is slightly different for ITO and RTO systems. However, given the marginal

disparity, and that both systems types are mainly using the same resources in engineering and production, a pathway for change that can be used for both systems is proposed. While there is a similar primary focus on the internal process, for both engineering and production, this is in conjunction with changes in the control mechanisms. And while the traditional material flow change process would then look at the supply side before the demand side, the reverse is here proposed, with an emphasis on ensuring uncertainty reduction with the customer to ensure due attention in ensuring fidelity of product specification and design.

The research has also identified specific aspects of the ITO and RTO systems that need due consideration. All ETO products in the study require a substantial share of manual work in engineering and production. The low volume and volatile market make it challenging to acquire the right number of specialized and skilled engineers and workers, and to establish sustainable work standards and routines, since customer specification and demand shifts from one year to the next. Low volumes and high uncertainty also make it challenging to establish good relationships with sub-suppliers and be their prioritized customer. However, there is a distinction in uncertainties between ITO and RTO systems.

In the new approach it is possible to identify uncertainties not just in engineering and production but also at the interface between the two, highlighting their interdependencies as well as their functional peculiarities. It is notable that, while they are both ETO systems, the ITO type is predominantly dominated by engineering uncertainties while the uncertainties in RTO types are due to production issues. ITO systems are developing specialized and advanced technical solutions that fulfil customer needs within given cost and time limitations. The projects are highly iterative and involve a range of changes throughout the order fulfilment process.

The problems faced by the ITO system is what the literature describes as a deep customer order penetration point, which is when the customer order requires new innovative design ideas, research and codes to be developed to fulfil the order (Gosling et al., 2017), which is unexplored terrain for both the customer and supplier. It was observed that this deep order interference, not only causes a new situation for engineering since existing knowledge and product configuration rules cannot be used, but also causes a ripple effect on all other actors in the ETO system, including sub-suppliers and their interaction. The level of unexplored terrain for engineering and production, as well as complex interactions between them, challenges the existing approach prescribed in the literature, which suggests a sequential supply chain reengineering approach to dampen uncertainty (Stevens, 1989; Mason-Jones and Towill, 1998).

RTO systems relate to existing designs in Gosling et al. (2017), and, hence, it should be possible to benefit from the creation of standard options, modules and platforms, product configurator systems, and flow efficient processes. However, there is typically an unstructured/limited standardized approach to transforming semi-customised orders into engineering and production activities, causing overengineering and less efficient use of capacity and resources, and lead time issues. This causes a dilemma since RTO products have lower margins than ITO products. The selected RTO products in the study are engineered and produced together with many other products. Each company is providing a wide portfolio of products with different architectural, functional, and physical characteristics (e.g. ITO, RTO and high-volume products). In addition, low volumes and high variety between projects make it challenging to standardize configuration options and streamline processes in engineering and production.

6. Conclusions

The aim of this paper was to develop a method to understand the systemic contributing factors of uncertainty in shipbuilding related first-tier suppliers that inhibit the effective and efficient delivery of ETO systems and to ascertain the change management pathway to reduce

uncertainties. The novel method developed identifies, categorizes and analyses uncertainties. The outputs of the method include a ranking of uncertainties for distinct ETO systems with their own attributes including uncertainty profiles. The application of the method to the four first-tier suppliers yielded an additional contribution, namely the ITO and RTO types, with ITO system uncertainties relating to innovative and customized projects, and RTO system uncertainties, which are more focused on products modified from existing designs.

Another contribution of the study is the extension of the 'uncertainty circle' model by differentiating between systemic factors of uncertainty associated with engineering and those related with production. In addition, while previous production focused research suggests a particular sequential approach to 'shrinking' the 'uncertainty circle', the consideration of both engineering and production indicates an alternative pathway starting with both process and control, followed by a similar analysis of demand, and finally supply.

The novel method allows for an initial mapping and comparison of different engineering and production decoupling configurations. The results show a classification of the two distinct ETO systems and a ranking of uncertainties for those two system types. A systemigram modelling and problem structuring method is also included to better illustrate and analyse the system wide implications of the uncertainties that are identified.

From a managerial perspective, the main contributions of this study are a structured approach for practitioners and academics to identify and analyse uncertainty in ETO industries, and the identification of two main system types in shipbuilding with empirically grounded descriptions of their top uncertainties. For ITO systems, a main concern for managers should be engineering and the interaction with customers in the specification and design stage. For RTO systems, there is a need to concentrate efforts on the mobilisation and execution of production activities. The method encourages managers to take a holistic approach to uncertainty profiling. The distinction between engineering and production issues makes this method well suited for engineering intensive industries such as shipbuilding supplies. Managers can use this method to evaluate their portfolio and compare uncertainties in different engineering and production decoupling configurations.

Although this study gives insight into the systemic factors of uncertainty in the shipbuilding supplies industry, it does have its limitations. Four companies and 11 products from one geographical region were studied and, although representative of the high-value add shipbuilding sector, care must be taken in generalizing the uncertainties identified to the wider shipbuilding supplies sector and other ETO industries. Future research may therefore involve a large-scale survey for data collection and statistical analysis allowing for comparison and generalisation among a larger sample of ETO shipbuilding companies, varying market characteristics and a broader geographical spread, potentially leading to a more generic understanding of uncertainty and its reduction, as well as the broader identification of the novel ITO and RTO system types. Such further research requires consideration of mitigation approaches to reduce uncertainty, including the creation of learning-cycle processes that will enable ITO and RTO systems to react to events in a more systematic and considered manner. Especially, there is a need to examine the issues that arise from interference between ITO and RTO systems built in the same value stream, and which solutions can mitigate uncertainties when radically different ETO system types are sharing the same resources and people. There can also be due consideration of the financial and resource implications, but also the benefits, of creating separate value streams for each type.

It is notable that the workshop participants, from first-tier shipbuilding organisations, did not highlight any external factors as causes of uncertainty. This is perhaps due to their 'business as usual' operational perspectives. External factors are a major uncertainty source in the globalized shipbuilding supplies industry, which clearly has been demonstrated in the situation with the Covid-19 pandemic creating a major disturbance. Hence, further research should seek to investigate

external factors related to market, facilities, assets, organisation and economy, and how they will require a more strategic perspective to developing resilient shipbuilding supply chains. This exploratory study develops a pathway and foundation to move towards more theory testing approaches, such as larger scale surveys.

Declarations of competing interest

None.

Appendix 1 Interview evaluation

Research Phase	Interview Feedback
Phase 1 – Determine customer order decoupling points <i>Do you have ETO products in your product portfolio? Can they be characterized as ITO or RTO?</i>	I1: “Yes, we are delivering both types of products, but mostly RTO”. I4: “Yes, we have mostly RTO projects, but some ITO projects. RTO are ‘standard’ products but require small design changes to satisfy the customer”. I5: “Most projects have a high level of innovation (ITO), but we also deliver repeat projects (RTO)”. I6: “most of the products we deliver are ITO types, but your distinction between innovation and redesign is not sufficiently specified”
Phase 2 identify and Categorise Sources of Uncertainty <i>Do these sources of uncertainty look familiar to you, and do you agree in the ranking?</i>	I1: “Yes, these sources of uncertainty are very familiar to me”. “The ranking seems to be correct, but Engineering lead times should be ranked higher up for ITO” I3: “Yes, but the commercial aspects related contracts seem to be missing in both tables. How the contract is defined is a major source for uncertainty. The dialogue with customers is also missing”. I4: “I recognize these sources of uncertainty, but where is design changes? Design changes is a main source of uncertainty”. I5: “Relationship management should be moved further up” I6: “What about the lack of competence to understand the customer/customer communication? The factor causing the highest uncertainty is the parallelism (of design and production)”.
Phase 3 – System based causal analysis <i>Do the Systemigrams capture the main concepts and relationships in the ETO delivery process that are impacted by uncertainties? Do you recognize any patterns regarding the position of the uncertainty sources in the systemigrams that are familiar?</i>	I1: “They are not wrong. Good capture” I2: “I recognize most of it” I3: “I understand the logic of the diagram and recognize the concepts and relationships, but where is sales in the diagram?” I4: “This is a nice mind map” “Relationship management for ITO should also include components suppliers and production technology system suppliers” I5: “The systemigrams should differentiate between concept design and detailed design. Concept design is much more important than detailed design” “Where is market, management, facilities and assets, organisation, and economy in the figure? These are boundary conditions that all uncertainty factors will depend on”. I6: “Intuitively, parts of the systemigrams are recognizable, while others are not”. “What causes uncertainty is the interfaces between the clusters”

Appendix 2. ITO top five uncertainty sources

UNCERTAINTY SOURCES	QUOTES FROM INTERVIEWS
1 Specification.	I1: “The main challenge related to specification is cost management, it is difficult to estimate costs for a prototype, and the consequences are huge if you miss by 20% on the cost estimate”. “It is difficult to make a specification because the equipment must fit the boat, and because there need to be an interface to all the other equipment on the boat” “Specification should also include involvement of suppliers” I3: “The contract type for ships are very different from the EPC contracts that are common in the offshore industry. The customers in EPC contracts takes much more responsibility for the risk involved in developing the products” I5: “Specification is wicked problem. The specification evolves during the fulfillment process. The fulfillment process starts with a very aggregated and open specification, and it is crucial to capture the stakeholders expectations in an early phase”. I6: “We sell a concept. The specification is still ongoing when engineering/production starts”. “The later the change comes the more fundamental it will be” “A key element is how to deal with the change, how it is communicated to the sub-suppliers”.
2 Supplier lead times.	I1: “It is difficult to estimate the demand and how much capacity that is required”. I4: “We end up in situations where we have 99% percent of what we need, but are missing one component with 10 weeks delivery time” I5: “Yes and no, this is challenging in good times, but not in bad times when market is low”. I6: Change orders will put extra pressure and cause uncertainty, also for the supplier system”.
3 Relationship management.	I3: “The process involves many iterations which are a major source of uncertainty”. “Lack of good dialogue and misunderstandings in the specification process are typical for unsuccessful projects” I4: “Engineering must be in close dialogue with the purchaser”. “It is very difficult to synchronize the collaboration between different departments” I5: “Relationships management is important, especially in order to understand the customer. We need to understand what he wants, and what is realizable within the prize he is willing to pay” I6: “We can end up with supplier relationships that not have been gradually cultivated and standardized over time. This creates uncertainty”.
4 Product structure.	I1: For ITO projects we should do a Front-End Engineering Design project first to define the structure. I3: The management of design revisions is a major source of uncertainty that is missing. I4: “Design changes is a main sources of uncertainty, and occur because the contract is not specified detailed enough, and because of interface problems with the other equipment on a ship”. “Use simple prototypes to enable early understanding and fruitful discussions in a multi-disciplinary team” I5: “The technology readiness level (TRL) is important. Products with low TRL is easier to realize in Europe”.
5 Engineering lead times.	I2: “Source no 5 Engineering lead times should be ranked higher up”. I4: “We should have an engineering process with clear gateways to ensure that things are ready. Delays creates much risks” I5: “We use way too much time on engineering”

Appendix 3. RTO top five uncertainty sources

UNCERTAINTY SOURCES	QUOTES FROM INTERVIEWS
1 Over engineering.	I2: "We do overengineering. We should use more time on simplification of designs" I3: "Unnecessary features that are added to the template from earlier projects results in overengineering" I4: "Yes, the engineers tend to include the last and best technology" I5: "RTO projects will almost always lead to over specifications. This is golden plated design".
2 Configuration.	I1: "Even if we make 100 of the same type per year, they will not have the same design" "Reduction of uncertainty depends on scalability, we need a much higher turnover of a product type in order to standardize" I2: "We can do less mistakes in RTO projects" I3: "We need better software tools for efficient engineering. We need to have complete control of design revisions" I5: "The architecture is still not standardized, and this create uncertainties in the interfaces between different systems" I6: "Yes, but there should not be an element of uncertainty in RTO project since the level of customer specification is low"
3 Lead times in production.	I2: "This should also cover the lead time for suppliers" I3: "The main solution is to rig for shorter throughput times in production. Then we become more flexible and can handle interruptions more easy" I6: "Production lead times is particularly relevant when there is an order change".
4 Lack of common rules.	I1: "We should establish the design rules early when we are entering a new market" I3: "Engineering must be more rigid and standardized". I4: "Person dependent engineering differences occurs that creates bad implications for production and testing. Components need to be modified in order to fit, the product becomes difficult to assemble etc." "Mistakes in design require more hours and more capacity in production and testing" I6: "Common rules are fundamental in order to reduce uncertainty. But common rules can be difficult to define"
5 Production Capacity.	I4: "Some demanding tasks can only be performed by certain operators that have long experience and the right skillset for that specific task. Demanding tasks that require specialist skills makes the capacity planning very demanding" I6: "There is a need for strategies to cope with the uncertainty such as hiring, outsourcing, combination or flexible internal solutions with employees"

References

- Aitken, J., Childerhouse, P., Deakins, E., Towill, D., 2016. A comparative study of manufacturing and service sector supply chain integration via the uncertainty circle model. *Int. J. Logist. Manag.* 27 (1), 188–205.
- Amaro, G., Hendry, L., Kingsman, B., 1999. Competitive advantage, customisation and a new taxonomy for non make-to-stock companies. *Int. J. Oper. Prod. Manag.* 19 (4), 349–371.
- Aramo-Immonen, H., Vanharanta, H., 2009. Project management: the task of holistic systems thinking. *Hum. Factors Man* 19, 582–600.
- Arafati, S., 2017. New Product Development and Supply Chain Management Alignment in Engineer-To-Order Companies. Masters Thesis, Politecnico di Milano.
- Blair, C.D., Boardman, J.T., Sauser, B.J., 2007. Communicating strategic intent with systemigrams: application to the network-enabled challenge. *Syst. Eng.* 10 (4), 309–322.
- Cannas, V.G., Gosling, J., Pero, M., Rossi, T., 2019. Engineering and production decoupling configurations: an empirical study in the machinery industry. *Int. J. Prod. Econ.* 216, 173–189.
- Checkland, P., 1999. Soft systems methodology: a 30-year perspective. In: Checkland, P., Scholes, J. (Eds.), *Soft Systems Methodology in Action*. Wiley, Chichester, England.
- Childerhouse, P., Towill, D.R., 2002. Analysis of the factors affecting real-world value stream performance. *Int. J. Prod. Res.* 40 (15), 3499–3518.
- Childerhouse, P., Towill, D.R., 2004. Reducing uncertainty in European supply chains. *J. Manuf. Technol. Manag.* 15 (7), 585–598.
- Childerhouse, P., Towill, D.R., 2011. Arcs of supply chain integration. *Int. J. Prod. Res.* 49 (24), 7441–7468.
- Christopher, M., Peck, H., 2004. Building the resilient supply chain. *Int. J. Logist. Manag.* 15 (1), 1–13.
- Daniel, L., Takagi, H., 2019. Overview of the Maritime Supplier Industry, Presentation at the Workshop on Trends and Challenges in Shipbuilding: A Special Look at the Maritime Equipment Industry, OECD Council Working Party on Shipbuilding. http://www.oecd.org/industry/ind/WP6-Workshop_Item_1.1.1_OECD_Secretariat.pdf.
- Dixit, V., Chaudhuri, A., Srivastava, R.K., 2019. Assessing value of customer involvement in engineered-to-order shipbuilding projects using fuzzy set and rough set theories. *Int. J. Prod. Res.* 57 (22), 6943–6962. <https://doi.org/10.1080/00207543.2019.1572928>.
- Emblemsvåg, J., 2014. Lean project planning in shipbuilding. *J. Ship Product. Design* 30 (2), 79–88.
- Emmel, N., 2013. Sampling and Choosing Cases in Qualitative Research: A Realist Approach. Sage.
- Evans, S., Jukes, S., 2000. Improving co-development through process alignment. *Int. J. Oper. Prod. Manag.* 20 (8), 979–988.
- Fabbe-Costes, N., Lechaptois, L., Spring, M., 2020. The map is not the territory: a boundary objects perspective on supply chain mapping. *Int. J. Oper. Prod. Manag.* Vol. ahead-of-print.
- Fundin, A., Bergquist, B., Eriksson, H., Gremyr, I., 2018. Challenges and propositions for research in quality management. *Int. J. Prod. Econ.* 199 (2018), 125–137.
- Gasparotti, C., Rusu, E., 2018. An overview on the shipbuilding market in current period and forecast. *EuroEconomica* 37 (3).
- Gosling, J., 2011. Flexibility Strategies for Engineer-To-Order Construction Supply Chains. Ph.D. thesis, Cardiff Univ., Cardiff, UK.
- Gosling, J., Naim, M.M., 2009. Engineer-to-order supply chain management: a literature review and research agenda. *Int. J. Prod. Econ.* 122 (2), 741–754.
- Gosling, J., Naim, M., Towill, D., 2013. Identifying and categorizing the sources of uncertainty in construction supply chains. *J. Construct. Eng. Manag.* 139 (1), 102–110.
- Gosling, J., Hewlett, B., Naim, M.M., 2017. Extending customer order penetration concepts to engineering designs. *Int. J. Oper. Prod. Manag.* 37 (4), 402–422.
- Gourdon, K., Steidl, C., 2019. Global Value Chains and the Shipbuilding Industry, OECD Science, Technology and Industry Working Papers, No. 2019/08. OECD Publishing, Paris. <https://doi.org/10.1787/7e94709a-en>.
- Hammer, M., 2004. Deep change: how operational innovation can transform your company. *Harv. Bus. Rev.* 84–93.
- Helseth, A., Mellbye, C.S., Jakobsen, E.W., 2018. Norwegian Maritime Equipment Suppliers 2018: key performance indicators and future expectations. *Norsk Industri*. <https://www.menon.no/wp-content/uploads/Maritime-equipment-suppliers-2018.pdf>.
- Hoekstra, S., Romme, J., 1992. *Integrated Logistics Structures: Developing Customer Oriented Goods Flow*. McGraw-Hill, London.
- Hong-Minh, S.M., Barker, R., Naim, M.M., 2001. Identifying supply chain solutions in the UK house building sector. *Eur. J. Purch. Supply Manag.* 7 (Issue 1), 49–59.
- Horna, E.G., 2018. The Two-Dimensional Customer Order Decoupling Point: Factors and Effects on Performance. Masters Thesis, Politecnico di Milano.
- Iakymenko, N., Brett, P.O., Alfnes, E., Strandhagen, J.O., 2020. Analyzing the factors affecting engineering change implementation performance in the engineer-to-order production environment: case studies from a Norwegian shipbuilding group. *Prod. Plann. Contr.* <https://doi.org/10.1080/09537287.2020.1837939>.
- Jiao, J., Helander, M.G., 2006. Development of an electronic configure-to-order platform for customized product development. *Comput. Ind.* 57 (3), 231–244.
- Kurtz, C.F., Snowden, D.J., 2003. The new dynamics of strategy: sense-making in a complex and complicated world. *IBM Syst. J.* 42 (3), 462–483.
- Mason-Jones, R., Towill, D.R., 1998. Shrinking the supply chain uncertainty circle. *IOM Contr.* 24 (7), 17–22.
- Mazoyer, B., Tzourio-Mazoyer, N., Mazard, A., Denis, M., Mellet, E., 2002. Neural bases of image and language interactions. *Int. J. Psychol.* 37 (4), 204–208.
- Mello, M.H., Strandhagen, J.O., 2011. Supply chain management in the shipbuilding industry: challenges and perspectives. *Proc. IME M J. Eng. Marit. Environ.* 225 (3), 261–270. <https://doi.org/10.1177/1475090211406836>.
- Mello, M.H., Strandhagen, J.O., Alfnes, E., 2015. Analyzing the factors affecting coordination in engineer-to-order supply chain. *Int. J. Oper. Prod. Manag.*
- Mello, M.H., Gosling, J., Naim, M.M., Strandhagen, J.O., Brett, P.O., 2017. Improving coordination in an engineer-to-order supply chain using a soft systems approach. *Prod. Plann. Contr.* 28 (2), 89–107.
- Mingers, J., Rosenhead, J., 2004. Problem structuring methods in action. *Eur. J. Oper. Res.* 152 (3), 530–554.
- Olhager, J., 2003. Strategic positioning of the order penetration point. *Int. J. Prod. Econ.* 85 (3), 319–329.
- Owen, J.H., Huang, N., 2007. Local improvements that degrade system performance: case studies and discussion for throughput analysis. *Int. J. Prod. Res.* 45 (10), 2351–2364.
- Parnaby, J., 1979. Concept of a manufacturing system. *Int. J. Prod. Res.* 17 (2), 123–135.
- Reips, U.D., Funke, F., 2008. Interval-level measurement with visual analogue scales in Internet-based research: VAS Generator. *Behav. Res. Methods* 40, 699–704.

- Rodrigues, V.S., Stantchev, D., Potter, A., Naim, M., Whiteing, A., 2008. Establishing a transport operation focused uncertainty model for the supply chain. *Int. J. Phys. Distrib. Logist. Manag.* 38 (5), 388–411.
- Rodrigues, V.S., Piecyk, M., Potter, A., McKinnon, A., Naim, M.M., Edwards, J., 2010a. Assessing the application of focus groups as a method for collecting data in logistics. *Int. J. Logist. Res. Applic.* 13 (1), 75–94.
- Rodrigues, V.S., Potter, A., Naim, M.M., 2010b. Evaluating the causes of uncertainty in logistics operations. *Int. J. Logist. Manag.* 21 (1), 45–64.
- Sanchis, R., Canetta, L., Poler, 2020. A conceptual reference framework for enterprise resilience enhancement. *Sustainability* 12 (4), 1464.
- Sanderson, J., Cox, A., 2008. The challenges of supply strategy selection in a project environment: evidence from UK naval shipbuilding. *Supply Chain Manag.: Int. J.*
- Semini, M., Haartveit, D.E.G., Alfnes, E., Arica, E., Brett, P.O., Strandhagen, J.O., 2014. Strategies for customized shipbuilding with different customer order decoupling points. *Proc. IME M J. Eng. Marit. Environ.* 228 (4), 362–372.
- Song, J.-S., Zipkin, P., 2003. Supply chain operations: assemble-to-order systems. *Handb. Oper. Res. Manag. Sci.* 11, 561–596.
- Steidl, C., Daniel, L., Yildiran, C., 2018. *Shipbuilding Market Developments Q2 2018*. OECD. <https://www.oecd.org/sti/ind/shipbuilding-market-developments-Q2-2018.pdf>.
- Stevens, G.C., 1989. Integrating the supply chain. *Int. J. Phys. Distrib. Mater. Manag.* 19 (8), 3–8.
- Strandhagen, J.W., Buer, S.V., Semini, M., Alfnes, E., Strandhagen, J.O., 2020. Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain. *Prod. Plann. Contr.* 1–16.
- Towill, D.R., Childerhouse, P., Disney, S.M., 2002. Integrating the automotive supply chain: where are we now? *Int. J. Phys. Distrib. Logist. Manag.* 32 (2), 79–95.
- Treille, S.D., Shapiro, R.D., Hameri, A.-P., 2004. From supply chain to demand chain: the role of lead time reduction in improving demand chain performance. *J. Oper. Manag.* 21 (6), 613–627.
- Vaagen, H., Kaut, M., Wallace, S.W., 2017. The impact of design uncertainty in engineer-to-order project planning. *Eur. J. Oper. Res.* 261 (3), 1098–1109.
- Van Der Vorst, J.G., Beulens, A.J., 2002. Identifying sources of uncertainty to generate supply chain redesign strategies. *Int. J. Phys. Distrib. Logist. Manag.*
- Vickers, G., 1965. *The Art of Judgement*. Chapman and Hall, London.
- Wikner, J., Rudberg, M., 2005. Integrating production and engineering perspectives on the customer order decoupling point. *Int. J. Oper. Prod. Manag.* 25 (7), 623–641.
- Williams, T., 2017. The nature of risk in complex projects. *Proj. Manag. J.* 48 (4), 55–66.
- Willner, O., Powell, D., Gerschberger, M., Schönsleben, P., 2016a. Exploring the archetypes of engineer-to-order: an empirical analysis. *Int. J. Oper. Prod. Manag.*
- Willner, O., Gosling, J., Schönsleben, P., 2016b. Establishing a maturity model for design automation in sales-delivery processes of ETO products. *Comput. Ind.* 82, 57–68.