Reducing risk exposure and financing cost by increasing delivery lead time

A Damen Shipyards case study

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By

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Master Thesis

In partial fulfilment of the requirements for the degree of

Master of Science
in Mechanical Engineering

at the Department Maritime and Transport Technology
of Faculty Mechanical Engineering
of Delft University of Technology
to be defended publicly on Wednesday June 19, 2024 at 12:30 PM.

Student number:	4443896	
MSc track:	Multi-Machine Engineering	
Report number:	2024.MME.8940	
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Date:	June 11, 2024	

This thesis is confidential and cannot be made public until June 19, 2024.

TU Delft

Preface

This thesis is the final part of the completion of the master's degree in Mechanical Engineering for the track Multi-Machine Engineering at Delft University of Technology. This research has been performed in cooperation with and is conducted at Damen Shipyards Gorinchem.

Near the end of my academic journey, I desired to dip into the maritime side of engineering and tackle complex, real-world problems. This led me to Damen, a company with an excellent reputation and a history of facilitating meaningful research. My fascination with large-scale engineering projects and complex systems influenced my decision to pursue this research. These interests were perfectly aligned with the challenges presented in this thesis, making it a deeply engaging and rewarding endeavour.

The journey had its share of challenges. I found it difficult to deal with the open-ended nature of the project, particularly in the beginning. Starting from scratch was tough, but the interviews and advice I got were crucial in helping me find my way. Another hurdle was learning a new programming language, VBA, which was essential for my research. Overcoming these obstacles demonstrates the importance of perseverance and support.

I hope this thesis will inspire the academic community to leverage data research in complex ERP systems and advocate for more integrated, centralised systems. Additionally, I expect for this work to influence the tugboat industry to adopt a process-oriented mindset, emphasising the elimination of rework.

This thesis would not have been possible without the greatly appreciated help of others. I want to thank Jasper Weterings for his invaluable weekly guidance and expertise and André Dekkers for providing a clear dot on the horizon for which to strive. My coworkers also deserve recognition for their insights, assistance, and the enjoyable conversations we shared at the coffee machine.

I am grateful to Mark Duinkerken, my thesis supervisor at the university, for his valuable feedback and encouragement to explore my research problem more deeply. I also want to acknowledge the important contributions of Rudy Negenborn, who provided constructive feedback during our progress meetings, which helped me maintain academic rigour.

On a personal note, I am forever grateful to my family, friends, and housemates for their unconditional love, support, and the healthy distractions they provided. Their encouragement was a constant source of motivation throughout this journey.

Thank you all for your support and belief in this project.

W.L.A. Siegmann
Delft, June 2024

Abstract

With fluctuating market demands, the tugboat industry confronts the challenge of adapting its supply chain to meet customer customisation needs while managing low order predictability. This study examines the shift from a Make-to-Stock (MTS) to three alternative production configurations based on the Assemble-to-Order (ATO) and Make-to-Order (MTO) configuration, focusing on the tugboat industry's need for flexibility in response to market changes and customer-specific requirements.

The core issue addressed is the trade-off between investment risk and customer satisfaction, as the proposed configurations increase delivery lead times. To quantify the costs associated with adapting delivery lead times, a Bill of Materials and Operations (BOMO) is utilised, combining the Bill of Materials (BOM) with the production sequence (Bill of Operations, BOO).

A mathematical algorithm is developed to calculate the financial effects of the configurations based on BOMO data. The model involves a three-step process: importing part data, merging BOM, BOO, supplier, and transport data into a BOMO dataset, and performing value analysis on the BOMO data to quantify risk exposure and financing costs over time.

The study's findings indicate that while increasing delivery lead times, the MTO configuration significantly reduces the risk exposure and financing costs. The BOMO is a strategic tool for analysing material costs and delivery lead times, providing insights into the financial implications of different production strategies. The research concludes that the MTO configuration is viable for Damen's tugboat production, balancing risk exposure, financing costs, and delivery lead times.

Keywords

- production strategy
- production configuration
- make-to-stock
- assemble-to-order
- make-to-order
- tugboat production
- risk exposure
- exposure profiles
- financial cost
- bill of materials
- bill of operations
- bill of materials and operations

List of abbreviations

Abbreviation	Definition
ASD	Azimuth Stern Drive
ATO	Assemble-to-Order
BOM	Bill of Materials
BOMO	Bill of Materials and Operations
BOO	Bill of Operations
CODP	Customer Order Decoupling Point
DSCS	Damen Song Cam Shipyard
DSGo	Damen Shipyards Gorinchem
ETO	Engineer-to-Order
KPI	Key Performance Indicator
MLT	Manufacturing Lead Time
MRP	Material Requirements Planning
MTO	Make-to-Order
MTS	Make-to-Stock
RSD	Reversed Stern Drive
SFPP	Supplier For Purchase Part
SSC	Start steel cutting
S&OP	Sales and Operations Planning
TBOM	Template Bill of Materials
YNBOM	Yard Number Bill of Materials

Contents

1 Introduction

1.1. Background and business context

In today's dynamic and ever-changing business environment, companies across various industries face the challenge of adapting their supply chain strategies to accommodate fluctuating market demands.(Arnold et al., 2008) This is particularly applicable to industries within the manufacturing sector, such as the tugboat industry.

Tugboats play a crucial role in supporting maritime transportation by assisting vessels in manoeuvering through ports, harbours, and other confined waterways, each requiring specific demands and customisation for the tugboat to be built. This emphasis on customisation is driven by the specific requirements expressed by customers in the industry. The tugboat industry is known for its low volume and low variety of products, but on the other hand, it faces low order predictability due to the high volatility of customer demand and unpredictable timing of customer orders. (Reiff, 2016)

The manufacturing process of tugboats is highly standardised, and periodical re-evaluation of the production configuration is essential to grow as a company. In the past few years, the assemble-to-order (ATO) production configuration has gained popularity in the maritime industry against the traditional engineer-to-order (ETO) production configuration. This popularity is due to its higher flexibility in responding to changes in market demand while still being able to provide customisation for the customer.

With a rich history dating back to 1927, Damen Shipyards has established itself as a leader in the maritime industry, delivering more than 175 high-quality vessels each year from 35 shipyards worldwide. (Damen, 2023) The company is well known for its philosophy of standardisation and its swift deliveries to customers worldwide. Their commitment to innovation and sustainability drives the motivation for this project from the company's perspective. Improving operational efficiency within Damen's shipbuilding processes accelerates innovation and paves the way for an earlier transition to sustainable solutions. This project contributes to Damen's mission of delivering cutting-edge vessels while contributing to our worldwide mission of reducing environmental impact.

The core activities of Damen encompass the design, construction, and maintenance of a wide range of vessels. Notably, Damen's production portfolio includes an annual output of more than 40 tugboats, making them the most sold vessel type within the company. Tugboats are part of the Workboats portfolio, engineered in Gorinchem and mainly produced in Song Cam, Vietnam.

1.2. Problem statement

The challenges in the increasing complexity of modern shipbuilding and its supply of materials, particularly within Damen's shipyards, are one of the causes of this project. At Damen, the industrial fabrication of tugs operates under a make-to-stock (MTS) configuration. With this configuration, vessel hulls are built to stock and later customised to the client's wishes.

Currently, the headquarters of Damen in Gorinchem decides which type of ship will be built for each production slot, usually 2-3 months before the production at the Song Cam shipyard. This decision is based on known client orders and market forecasts - also called the Sales & Operations Planning (S&OP).

The primary strategy is to build ships using the MTS production configuration, which accounts for a forecasting window of almost two years, showing a possible risk of inaccurate forecasting. Damen should ideally shorten this forecasting, considering the ever-evolving market demands and unforeseeable market disruptions—such as the COVID-19 pandemic, the 2021 global energy crisis, the ongoing war in Ukraine, and the recent situation in the Red Sea. This way, Damen's tugboat production can better adapt to these market changes.

In addition, customers may express interest or place orders before the ship's completion. This proactive approach allows Damen to cater to clients with specific customisation requirements or who prefer to secure their orders in advance. In such cases, Damen can offer configurable options even before the boat is fully assembled, enabling a more tailored and responsive manufacturing process. This enhances customer satisfaction by accommodating individual preferences and gives Damen a competitive advantage in meeting dynamic market demands.

This makes the baseline for this problem a dynamic strategy that starts for each vessel as a Make-to-Stock vessel and can dynamically adapt to a more order-driven production configuration, as presented in Figure 1.1. This baseline production configuration is feasible in a scenario with high customer demand, but will it be feasible when this demand decreases?

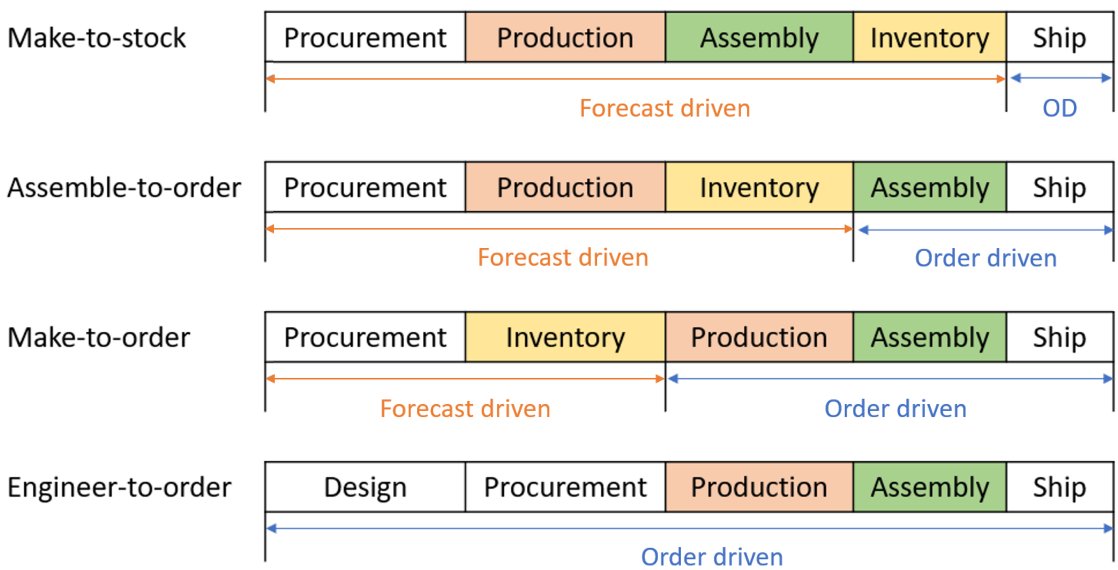

Figure 1.1: The four production configurations. (Arnold et al., 2008)

A possible solution is shifting the standard approach from a Make-to-Stock configuration to an Assemble-to-Order configuration, where sub-assemblies are prefabricated, the material is available at the yard, and the assembly can start when a customer orders a vessel. Implementing this configuration reduces the risks of inaccurate forecasting, and overall capital investment costs are lower. (Arnold et al., 2008)

The downside of this production configuration is that the customer's delivery lead time is increased, making this problem a trade-off between investment risk and customer satisfaction. The problem that arises is the main driver for this thesis and a gap in the literature. It is currently unknown what the relation is between investment costs and adapting the delivery lead time.

The investment costs can be related to the material costs accumulated over the project's duration. (Wouters, 1991) Additionally, there is a knowledge gap between the availability of materials and the costs of having the materials stocked at a particular time in the total production phase.

A Bill of Materials and Operations (BOMO) creates insight into material costs by combining the Bill of Materials (BOM) module with the production sequence - the Bill of Operations (BOO). (Jiao et al., 2000) Thus, a systematic, data-driven decision-making tool that combines the S&OP, BOM and the building process is needed to relate the investment costs to delivery lead time.

1.3. Challenge

To the best of the author's knowledge and according to a recent literature study, the link between investment costs and delivery lead time with the help of a BOMO has not been made yet. It is a vital module for creating insight into production processes; therefore, it should be further used to develop a strategic decision tool to support the decision to switch to an ATO production configuration.

The practical side of this project involves generating a mathematical algorithm that calculates the benefits of implementing the ATO production configuration within the existing MTS production process based on the BOMO data. This algorithm could help decide which materials must be in stock or which suppliers to prioritise collaborating with, reducing the supplier's lead time to the yard.

Therefore, the goal is to develop a data-driven method to calculate the cost of adapting delivery lead times.

1.4. Research questions

This research proposes a method of quantifying the costs of adapting the delivery lead time within a production configuration based on data available by the Bill of Materials and Operations. To guide this research, the following main question and supporting sub-research questions (SRQs) will be addressed:

How can the costs of adapting delivery lead time be quantified with the help of the Bill of Materials and Operations when implementing a different configuration within Damen's tugboat production?

1. *What are delivery lead time costs, and how does this relate to the production configuration?*
2. *What is the Bill of Materials and Operations, and what is the relationship to the delivery lead time costs?*
3. *What are the key aspects of Damen's tugboat production and which data is available?*
4. *How can the tugboat production be modelled, and what are the key data elements?*
5. *How can the model be validated and how does this relate to the standard method to calculate delivery lead time adaption?*
6. *What are the costs of delivery lead time adaption for Damen's tugboat production?*

1.5. Methodology

The proposed approach to answering the research questions is shown in Figure 1.2. Chapter 1 serves as an introduction to the identified problem. In Chapter 2, an exploration of the relevant literature is conducted. The analysis of the Damen company is discussed in Chapter 3. Chapter 4 introduces a proposed BOMO calculation model. The validation and verification of the model are detailed in Chapter 5, followed by the study outcomes in Chapter 6. Finally, Chapter 7 encompasses the conclusion and discussion, answering the main research question.

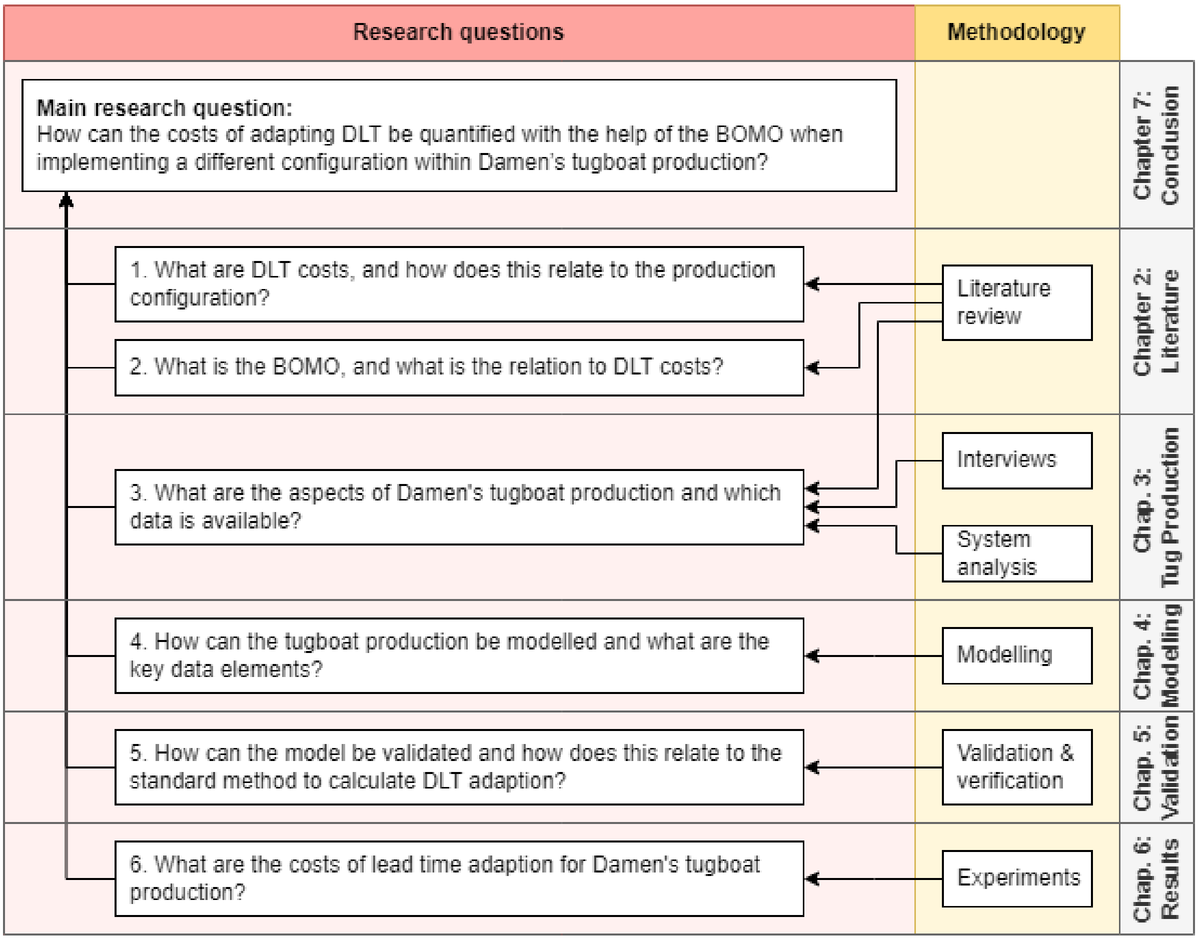

Figure 1.2: Methodology overview

2 Literature

2.1. Introduction

The literature review chapter examines the key concepts upon which this study is built. This exploration aims to provide a comprehensive understanding of the perspectives of the existing literature, laying a foundation for the subsequent chapters. Section 2.2 discusses the topics of delivery lead time and the ATO production configuration to answer the first sub-research question. This is followed by the Bill of Materials and Operation description in Section 2.3, which answers sub-research question 2.

2.2. Lead time and production configuration

In a serious competitive market, a winning production configuration holds significant importance. Such a configuration must fulfil or exceed customer expectations and ensure fast and on-time delivery of products. (Sen et al., 2000) This section will answer the first research question:

What are delivery lead time costs, and how does this relate to the production configuration?

To answer this question, two terms must first be introduced: lead time and the customer order decoupling point (CODP). Then, the four main production configurations are presented along with their distinctive characteristics. Finally, the Assemble-to-Order configuration is discussed, emphasising the maritime industry. The general supply chain process that is frequently referenced is illustrated in Figure 2.1, where material cost increases over time, while customisation options for the customer decrease over time.

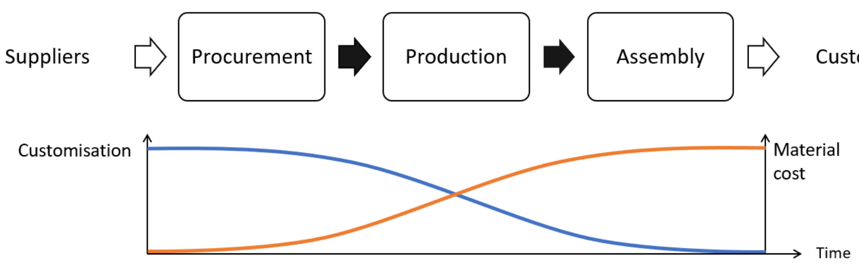

Figure 2.1: The supply chain process in the shipbuilding industry. (Derived from Chu et al., 2021, Meyr et al., 2008 and Wemmerlöv, 1984)

2.2.1. Lead time and CODP

Lead time is the time it takes for materials or products to move from one moment in the supply chain process to another. As visualised in Figure 2.2, there are various ways of identifying lead time:

- Supplier lead time: The time between an order is placed at the supplier to the moment the product is delivered at the production location;
- Production lead time: The time between the start of production and the moment the product is delivered at the assembly location;
- Assembly lead time: The time between the start of assembly and the moment the product is delivered at the customer.

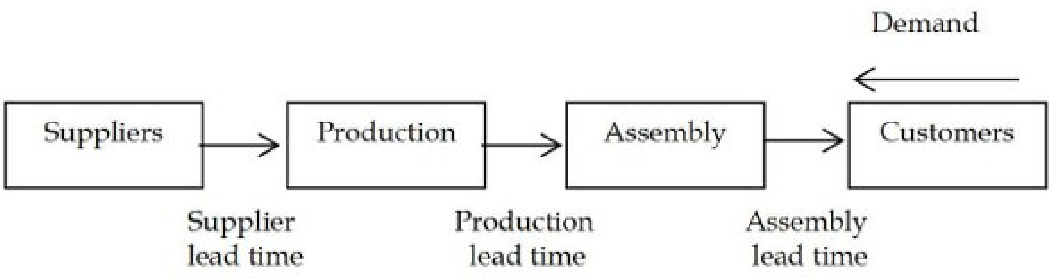

Figure 2.2: Supply chain lead time. (Dolgui et al., 2008)

From a customer's perspective, lead time can be considered the time they have to wait for their product to arrive. This is called the delivery lead time: the time between the moment a customer places an order and the moment of delivery. The moment an order is placed is when the customer penetrates the manufacturer's supply chain process, commonly referred to as the customer order decoupling point (CODP). (Hoekstra et al., 1992, Naylor et al., 1999)

Olhager (2003) and Amir (2011) discuss the role of the CODP for the manufacturer and states that the placement of the CODP has a strategic impact on the manufacturing process. By placing the CODP forwards in time, a competitive advantage can be gained regarding price, delivery speed and reliability. This configuration increases reliance on demand forecasting, which can put the manufacturer at a disadvantage when the market is unpredictable and changes a lot. (Olhager, 2012; Chen et al., 2000)

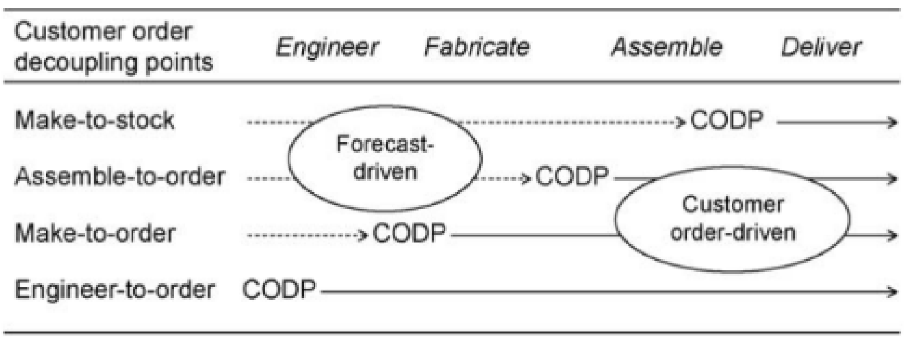

Figure 2.3: Different placements of the CODP. (Olhager, 2010)

By placing the CODP backwards in time, a competitive advantage can be gained regarding product range and quality, but at the cost of a longer delivery lead time. ElMaraghy et al. (2013) argue the importance of the right amount of variety in products for a manufacturer and that too much variety can be bad. Thus, the placement of the CODP is a key factor in the success of a business, which relates to many different variables in manufacturing processes and supply chains.

2.2.2. Production configurations

The four basic configurations for production are engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO) and make-to-stock (MTS), and the different characteristics can be seen in Table 2.1. (Arnold et al., 2008) These configurations can be distinguished by their customer involvement, the CODP placement and the delivery lead time length, as seen in Figures 2.3 and 2.4.

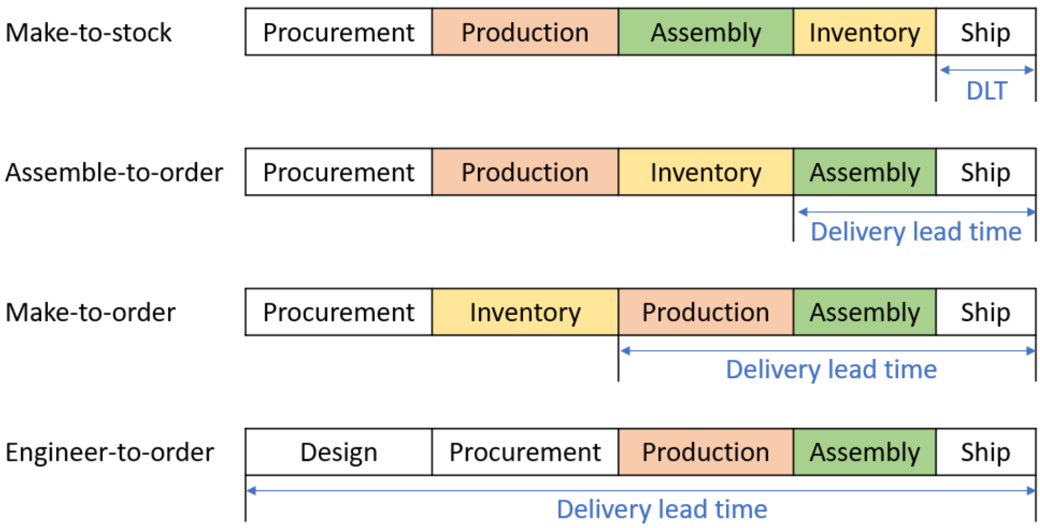

Figure 2.4: The four basic production configurations and their delivery lead times. (Arnold et al., 2008)

Aspect	Make-to-stock	Assemble-to-order	Make-to-order/ Engineer-to-order
Customer input	🔴	🟡 🟡	🟢 🟢 🟢
Lead time	🟢	🟡 🟡	🔴 🔴 🔴
Product variety	🟢 🟢 🟢	🟡 🟡	🔴
Production volume size	🟢 🟢 🟢	🟡 🟡	🔴
Production planning	Forecasting	Forecasting and order-driven	Order-driven
Handling demand uncertainty	Safety stock units	Overplanning of components and subassemblies	Little uncertainty exists

Table 2.1: Relative characteristics of MTS, ATO, MTO and ETO production processes. (Olhager, 2010; Wemmerlöv, 1984)

Thus, the production configuration is the strategic decision on when a customer penetrates the production process, and products are tied to customer requirements. The placement of the CODP and has a direct effect on delivery lead time. By placing the CODP forward in time, delivery lead times to the customer are reduced to gain a competitive advantage. However, this increases reliance on accurate forecasting and reduces product variety and customisation.

It is shown that the ATO production configuration is a better fit for coping with a volatile market than the traditional ETO configuration due to the reduced delivery lead time. Figure 2.5 illustrates how the CODP is positioned in the broader supply chain, as described in Chapter 1. It also shows that customisation options decrease over time, while material costs increase.

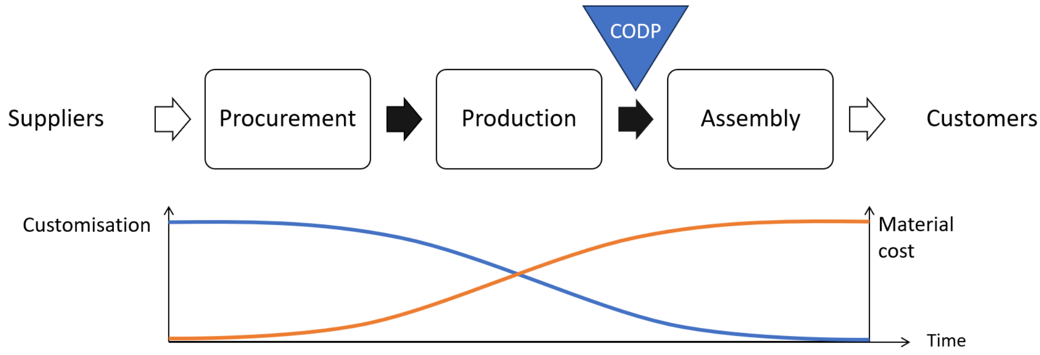

Figure 2.5: Placing the order decoupling point in the supply chain with ATO configuration. (Derived from Arnold et al., 2008, Olhager, 2010 and Wemmerlöv, 1984)

2.2.3. ATO production

Over the past decades, much research has been done on the operational side of production configurations. (Atan et al., 2017) In a simplified way, assemblies can be seen as sets of components which can be combined to form a portfolio of end-products. (Nadar et al., 2014) Figure 2.6 shows how stocked components can be combined into different end-products; the more combinations possible, the greater the variety of products.

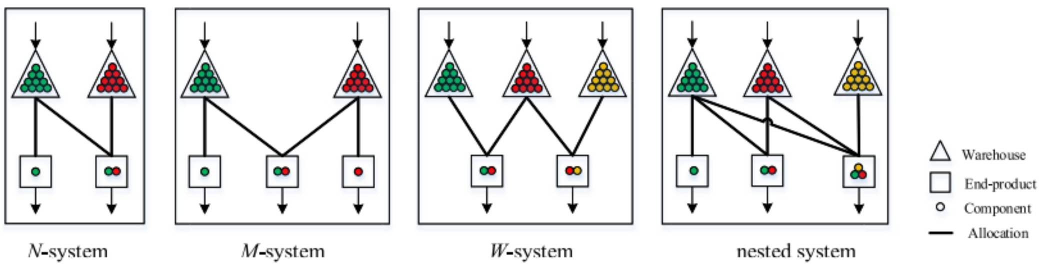

Figure 2.6: Different configurations for ATO systems. (Nadar et al., 2014)

Modularity

When dealing with large assemblies, end-products are often a combination of different components and sub-components that come together to create a whole. This relation process between all components can be seen as a work breakdown structure (WBS) or system breakdown structure (SBS), where a project or system is divided into smaller, more manageable tasks.

The breakdown structure of an assembly process is often referred to as product platform family or product architecture. (Deck, 1997) By analysing the product as a combination of modules, the overall performance of the production process can improve, the supply chain can become more agile and can be better at reacting to volatility in the market. (Saeed et al., 2019; Xu et al., 2012)

To break down the end product and understand its components, it is first divided into modules. These modules are the primary components that make up the final product. Each module has a specific task and physical connection with other modules. For example, a car is assembled from a steel body structure, a chassis, an engine, etc.

Further breaking down the modules, we have sub-components or ”part families”. (Seepersad et al., 2000) For instance, an engine module consists of shafts and gears that serve specific functions within the module or contribute to the overall functionality of the end product.

Breaking down further, parts within part families can be differentiated based on size or shape, until each part in a product has its own manageable task.

This hierarchical presentation of the end product forms a branch-like structure, which visualises the interconnections and interdependence of the different elements involved in the assembly process. The number of levels in the tree-like structure represents the level of modularity in the end product. Figure 2.7 shows an example of a product family tree at Volkswagen.

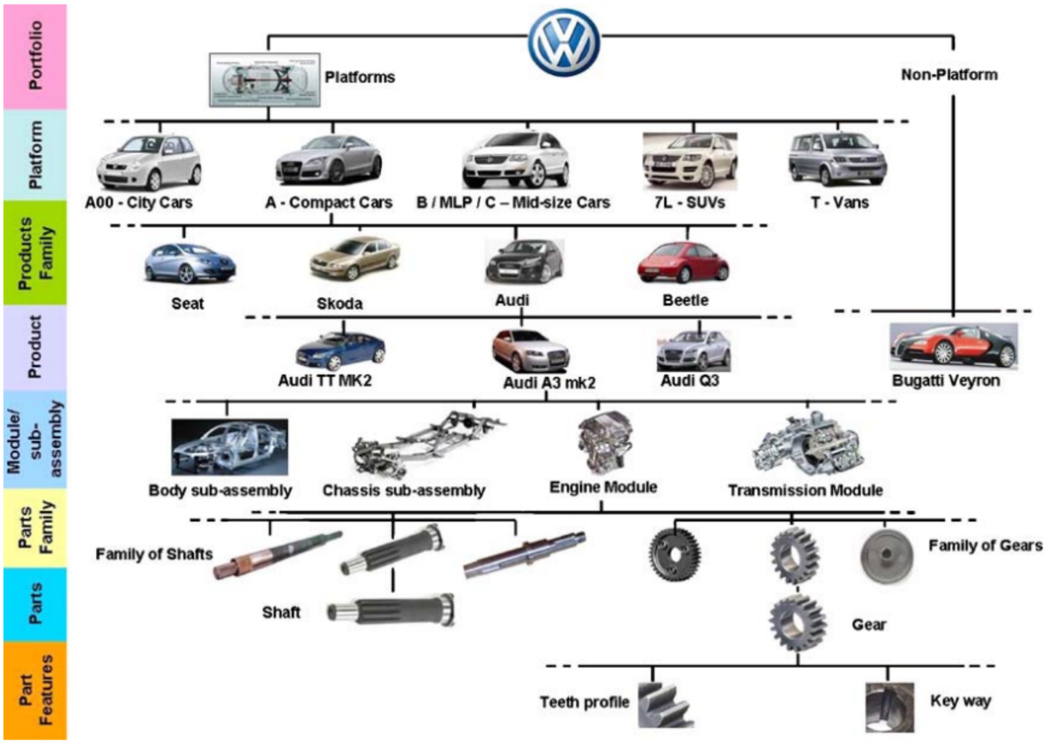

Figure 2.7: The product platform family tree of car models at Volkswagen. (ElMaraghy, 2009)

Commonality

Another crucial aspect of the breakdown of end products in an enterprise with a wide portfolio of different products is the concept of commonality. Commonality refers to the shared characteristics or standardised features along components within product families and has several advantages to the production process.

Firstly, commonality reduces the complexity of handling many unique components, thus simplifying the production process. It allows manufacturers to optimise production lines, increase revenue, and improve resource allocation and operational efficiency. (Gerchak and Henig, 1986)

Secondly, commonality leads to improved inventory management. When multiple products share common components, the number of unique parts is reduced throughout the enterprise. These reductions help minimise inventory costs, decrease the risk of obsolete parts, and improve the efficiency of supply chain operations. (Mohebbi and Choobineh, 2005)

Thirdly, manufacturers can quickly assemble products by drawing from a pool of shared components, which reduces lead times and increases the agility of the supply chain. (Hillier, 2002)

Lastly, commonality enables better utilisation of resources and expertise within the organisation. When production workers become familiar with a common set of components and share the same machines to operate, training time is reduced and overall productivity increases, also known as the learning curve. (Heizer and Render, 2012)

ATO shipbuilding

To implement the ATO production configuration, knowing what the manufacturing process of building a tugboat entails is essential. In the broader supply chain scheme, manufacturing is the step from procuring raw materials and components to a full product. This is illustrated in Figure 2.8.

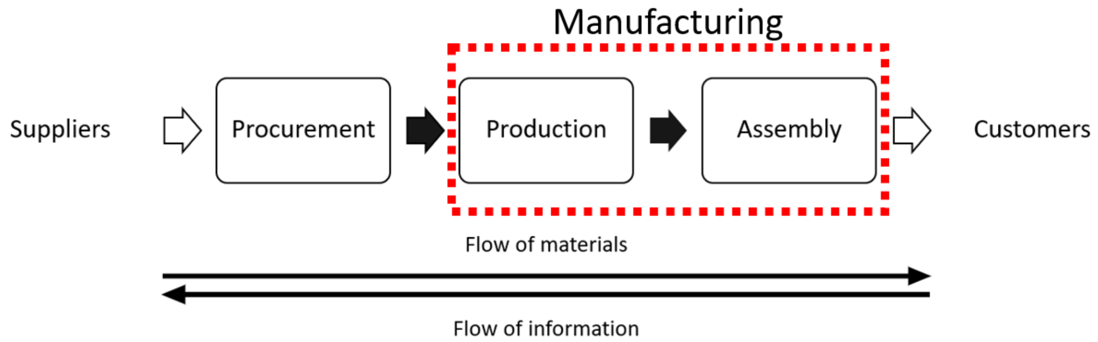

Figure 2.8: The manufacturing process within the supply chain.

The construction of ships consists mostly of constructing a hull and installing components onto the hull until a full ship is erected. The hull construction process can be divided into pre-fabrication, panel fabrication, section production, block assembly and hull assembly. (Rose and Coenen, 2016) An example of how a tugboat is built up out of blocks and sections is shown in 2.9

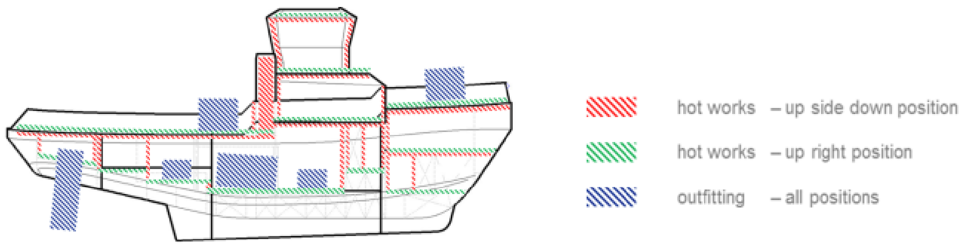

Figure 2.9: A tug split into blocks and sections. (Reiff, 2016)

Following the hull construction phase, non-structural parts, such as engines, thrusters, valves, pipes, ducts and cables, are installed onto the structural parts of the hull. This action is called outfitting and is done in several phases of the hull construction. (Reiff, 2016) An example of building a large ship hull with a modular approach is illustrated in Figure 2.10.

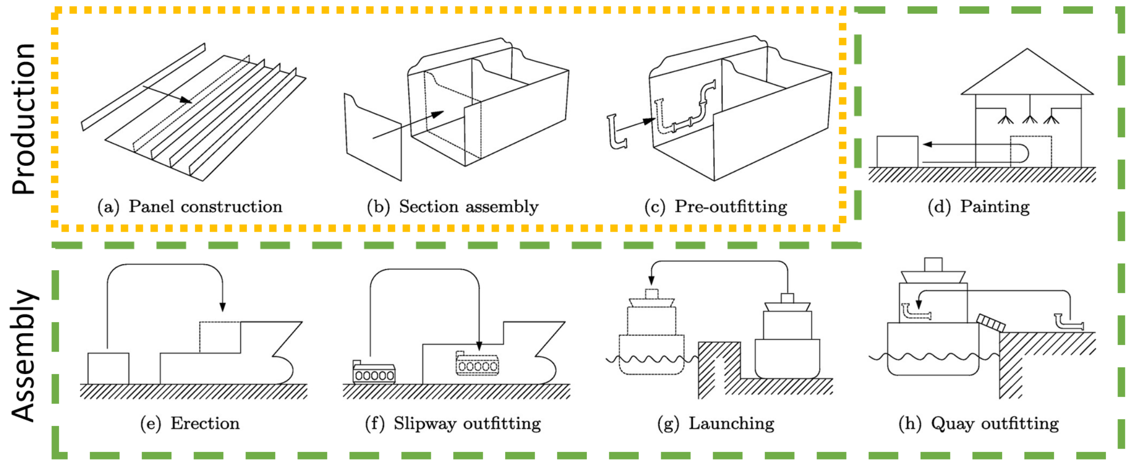

Figure 2.10: Main shipbuilding activities and the relation to ATO production. (Derived from Rose and Coenen, 2016)

(a) In the panel construction phase, steel plates are cut into panels and profiles, which are then welded together for panel sections.

(b) In the section assembly phase, panels are welded together to form the building blocks of the ship

(c) In the pre-outfitting phase, pipes, ducting, cable trays and other equipment is installed into the sections.

(d) After that, the partly finished sections are transported to the paint shop and painted.

(e) The building blocks are erected on the slipway to form the ship's hull.

(f) Then, the hull is outfitted on the slipway with big components such as engines or thrusters.

(g) When the outfitting is done, the ship is launched into the water and moored at the quay.

(h) And to finalise, the last components are assembled onto the ship at the quay.

The ATO production configuration could be implemented by splitting this manufacturing process into production and assembly. In the manufacturing process, it can be seen that in step d, the colour of the ship is determined. It is logical that this step should be done after an order is tied to a customer. Therefore, steps a-c can be done in the production phase, and steps d-h in the assembly phase.

2.2.4. Delivery lead time and ATO production

Thus, the delivery lead time of ships built with an ATO production configuration depends on the placement of the CODP within the production planning. In the cases presented, this is after hull blocks are produced, which means that the shipyard has a stock of hull blocks and other components and waits for customer orders.

Another option is to place the CODP further in time, e.g. after hull completion. This does add higher risks and more material value that is dedicated to a certain ship type, but vessels can be delivered to the customer faster. The material value and relation to the delivery lead time is discussed more thoroughly in the next section.

2.3. Bill of Materials and Operations

The Bill of Materials and Operations (BOMO) creates insight into material availability by combining the Bill of Materials (BOM) and the production sequence, often referred to as Bill of Operations (BOO). The data of the BOMO can be analysed to support the strategic decision of the CODP and the delivery lead time.

This section will answer the following research question:

What is the Bill of Materials and Operations, and what is the relationship to the delivery lead time costs?

To answer this question, the BOM and BOO will be treated in the broader perspective of material management and the relationship with other supply chain activities. Followed by the BOMO and how the BOMO can be generated from the BOM and BOO. Lastly, the possibility of the BOMO will be explored in relation to delivery lead time.

2.3.1. Material management

Effective material management is crucial for organisations to ensure smooth production processes, meet customer demand, and optimise resources. (Arnold et al., 2008) This section will focus on the processes of Sales & Operations Planning (S&OP), Material Requirements Planning (MRP), and the Bill of Materials (BOM) and especially how the BOM aids in establishing a production timeline, which determines procurement needs based on production lead time. Their relationship is visualised in Figure 2.11.

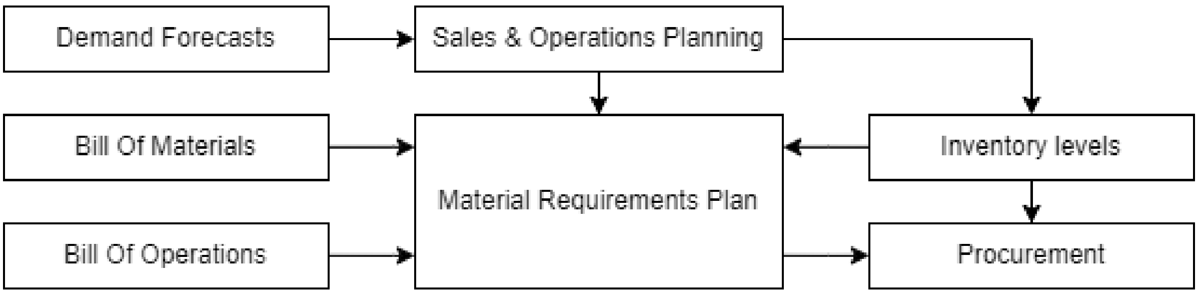

Figure 2.11: The relationship between supply chain activities, derived from (Arnold et al., 2008).

Sales & Operations Planning

S&OP is the strategic process that aligns sales forecasts with production capabilities to achieve business objectives, such as business, finance and marketing. (Arnold et al., 2008) By forecasting sales, S&OP balances the inbound and outbound of materials and provides critical input for material planning, enabling organisations to estimate future demand and align procurement accordingly. (Pereira et al., 2020) The output of the S&OP is a plan for how many units of each end item will be produced in the coming period. This information is communicated with the Material Requirements Plan.

Material Requirements Plan

The MRP is the management of material inventories and procurement based on the S&OP. (Gross, 2019) It uses the sales forecast from S&OP, the BOM and inventory levels to calculate the quantities and timing of materials needed. (Arnold et al., 2008) MRP considers lead times, safety stock, and production schedules to generate accurate material requirements and procurement schedules. It ensures materials are available when needed, minimising stockouts and excess inventory.

Bill of Materials

The BOM is defined as "items or raw materials that go into the product". (Garwood, 1990). It is a comprehensive list of all components, parts, and materials required to manufacture a specific product. Table 2.2 presents an example of the BOM data. The BOM structure outlines the hierarchical components within the product, detailing the quantity and description of all the components in the product, as shown in Figure 2.12. The BOM serves as a blueprint for production, providing clarity on the materials needed for each manufacturing stage. It also identifies dependencies between components, allowing for accurate scheduling and procurement planning. (Arnold et al., 2008)

Hierarchy Level	Parent Item	Component Item	Quantity per
1	Souvenir Clock	Desk Clock	1
1	Souvenir Clock	Paper Box	1
1	Souvenir Clock	Label Sticker	1
.2	Desk Clock	Body	1
.2	Desk Clock	Frame	1
..3	Body	Hands	1
..3	Body	Dial	1
..3	Body	Spacer	1
..3	Body	Movement	1
..3	Body	Screw	4
..3	Frame	Base	1
..3	Frame	Front Plate	1
..3	Frame	Label Sticker	1
...4	Movement	Gear Set	1
...4	Movement	Transmission	1
...4	Movement	Core	1
...4	Movement	Case	1
...4	Movement	Cover	1

Table 2.2: The BOM data of a souvenir clock. (Jiao et al., 2000)

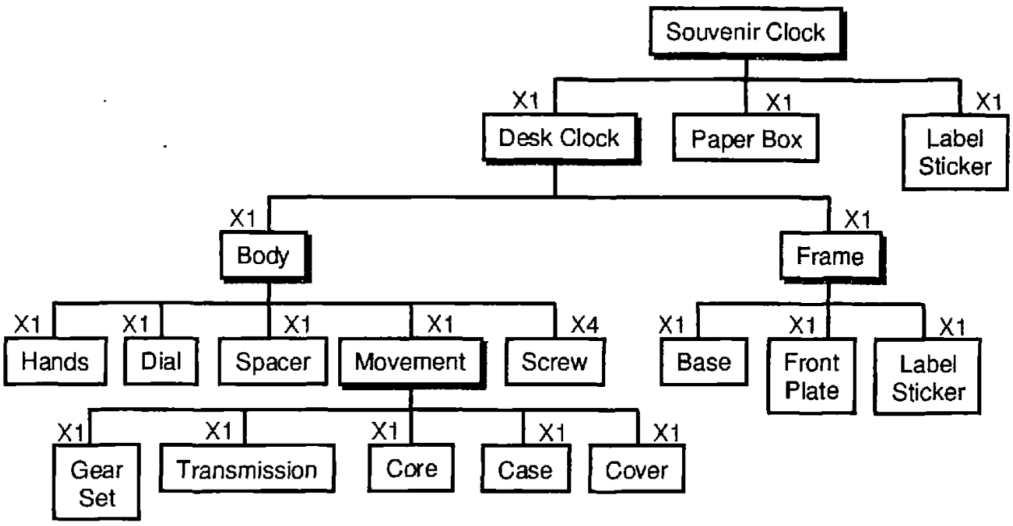

Figure 2.12: The BOM structure of a souvenir clock. (Jiao et al., 2000)

The BOM plays a crucial role in establishing a production timeline. Each component in the BOM has its own production lead times that indicate the time required for procurement, transport or manufacturing. The manufacturing lead times are specified in the Bill of Operations (BOO), which is discussed in the next section.

Bill of Operations

Similar to the BOM, which describes the structure of the product itself, the Bill of Operations (BOO) describes the structure of the production of a product. (Jiao et al., 2000) It defines the sequence of operations performed during production and steps required to assemble the end-product. An example of BOO data is shown in Table 2.3.

Operation	Work Center	Runtime (min/item)	Fixture/ Setup
Packaging & Inspection (A5)	WC-A5	1.5	
Kitting (K7)	WC-K7	1.0	
Clock Assembly (A4)	WC-A4	14.0	A4-F
Kitting (K6)	WC-K6	1.0	
Paper Box Preparation (A2)	WC-A2	2.0	
Kitting (K4)	WC-K4	4.5	
Frame Assembly (A3)	WC-A3	11.5	A3-F
Kitting (K5)	WC-K5	1.0	
Movement Assembly (A1)	WC-A1	11.0	A1-F
Kitting (K3)	WC-K3	4.5	
Base Fabrication (M1)	WC-M1	12.5	M1-F
Front Plat Fabrication (M2)	WC-M2	14.5	M2-FS
Kitting (K1)	WC-K1	9.0	
Printing (M3)	WC-M3	3.0	
Kitting (K2)	WC-K2	2.0	

Table 2.3: The BOO data of a souvenir clock. (Jiao et al., 2000)

Bill of Materials and Operations

The product structure data and operations information can be integrated into a data model called Bill of Materials and Operations (BOMO). By combining the BOM and BOO, multiple valuable analyses can be made, such as manufacturing or materials cost analysis. (Jiao et al., 2000).

This is possible by adding parameters and variables to the products in the BOMO. The possible input parameters to analyse manufacturing costs are labour rates, overhead rates and runtime, which are processed to calculate each operation's labour costs and overhead costs. For material costs, the input parameters can be unit cost and quantity to compute the material cost for each raw material in the BOMO.

Table 2.4 shows a cost analysis of the BOMO data for the souvenir clocks. Hereby the manufacturing costs and material costs are determined by the combination of the BOM and BOO dataset.

		Manufacturing Costs					Material Costs			
Operation	Work Center	Labor Rate ($/hour)	Overhead Rate ($/hour)	Runtime (min/item × Lot Size)	Labor Cost ($)	Overhead Cost ($)	Raw Material	Unit Cost ($/item)	Quantity Quan. per (Volume)	Material Cost ($)
Packaging & Inspection	WC-A5	7.0	7.5	1.5 × 5	0.875	0.938				
Kitting	WC-K7	5.0	8.0	1.0 × 5	0.417	0.667				
Clock Assembly	WC-A4	11.0	8.5	14.0 × 5	12.83	9.917	Hands (I_{111})	0.1	1 × 5	0.5
Kitting	WC-K6	5.0	8.0	1.0 × 5	0.417	0.667	Spacer (I_{113})	0.05	1 × 5	0.25
							Screw (I_{115})	0.03	4 × 5	0.6
Paper Box Preparation	WC-A2	5.0	5.0	2.0 × 5	0.833	0.833	Paper Box (I_2)	0.3	1 × 5	1.5
Kitting	WC-K4	5.0	8.0	4.5 × 5	1.875	3.0				
Frame Assembly	WC-A3	8.5	12.0	11.5 × 5	8.146	11.5				
Kitting	WC-K5	5.0	8.0	1.0 × 5	0.417	0.667				
Movement Assembly	WC-A1	11.0	11.0	11.0 × 5	10.083	10.083	Gear Set (I_{1141})	0.24	1 × 5	1.2
Kitting	WC-K3	5.0	8.0	4.5 × 5	1.875	3.0	Transmission (I_{114})	0.2	1 × 5	1.0
							Core (I_{1143})	0.98	1 × 5	4.9
							Case (I_{1144})	0.18	1 × 5	0.9
							Cover (I_{1145})	0.18	1 × 5	0.9
Base Fabrication	WC-M1$_1^*$	9.0	22.0	(12.5+3.0) × 5	11.625	28.417	Base (I_{121})	0.25	1 × 5	1.25
Front Plate Fabrication	WC-M2$_2^*$	9.0	22.0	(14.5+2.5) × 5	12.75	31.167	Front Plate (I_{122})	0.32	1 × 5	1.6
Kitting	WC-K1	5.0	8.0	9.0 × 5	3.75	6.0				
Printing	WC-M3	7.0	18.0	3.0 × 2 × 5	3.5	9.0	Dial (I_{112})	0.4	1 × 5	2.0
Kitting	WC-K2	5.0	8.0	2.0 × 2 × 5	1.667	2.667	Label Sticker (I_{12})	0.05	2 × 5	0.5
				Sub Total =	**71.06**	**118.523**				**17.1**
				Totals =				**206.683**		

Table 2.4: The cost analysis of BOMO data of a souvenir clock. (Jiao et al., 2000)

2.3.2. BOMO and delivery lead time

As stated in section 2.2, delivery lead time depends on when the assembly phase begins within the manufacturing process. Until that moment on the production timeline, the product is partially finished, and production is halted until a customer order arrives. The holding of sub-assembly can be seen as ”sleeping” capital that is not generating revenue. This capital is directly related to the material cost of the sub-assemblies.

The material costs of the sub-assemblies are effectively the cumulative costs of all the subordinate parts within the sub-assemblies. When the delivery lead time is reduced, the cumulative costs rise and vice versa. This results in a cost-benefit relation between fast delivery and material cost, a relation that can be extracted from the BOMO.

This relation can be visualised with the cost analysis of the BOMO, as it shows the manufacturing and material costs for each operation. These costs can be plotted over the total runtime of the manufacturing process. An example of material costs plotted over runtime is shown in Figure 2.13. This is where the relationship between the costs of delivery lead time and the BOMO becomes clear.

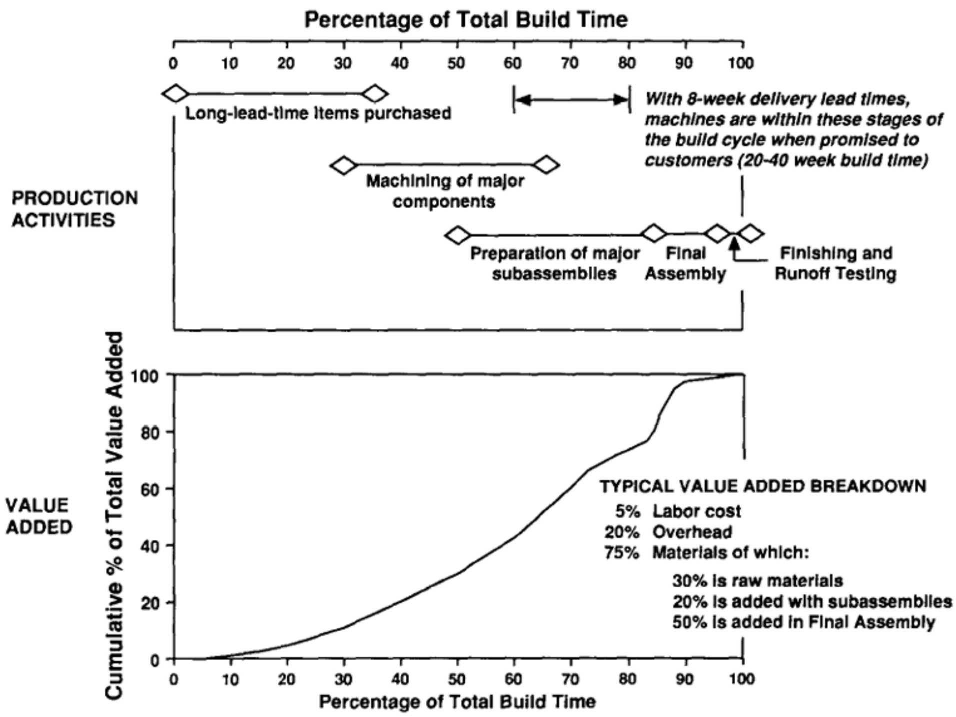

Figure 2.13: The manufacturing process in the machine tool industry. (Raturi et al., 1990)

2.4. Conclusion

Thus, the answer to the first research question is that the delivery lead time depends on the placement of the CODP within the production planning. The ATO configuration has a longer delivery lead time than the MTS configuration but reduces the risk of inaccurate forecasting. The delivery lead time costs are related to the production process’s material costs.

The answer to the second research question is that the BOMO is a comprehensive list of all components, parts and materials and their manufacturing lead time or activity timeline within the production process. The material value of this process can be plotted on a value-added curve. With this information, an accurate value analysis for the total runtime of the process, such as the costs of shortening or extending the delivery lead time.

3

Tugboat production

3.1. Introduction

This chapter discusses the system analysis of tugboat production and the company analysis of Damen. Damen, renowned for its innovative and diverse maritime solutions, is a key player in the global shipping industry. By closely outlining the company's tugboat production, this chapter aims to provide a nuanced understanding of the company's processes and answers the third research question:

What are the key aspects of Damen's tugboat production and which data is available?

The contents of this chapter are substantiated by previous research done by Reiff (2016) and interviews conducted within the company. These interviews are summarised in Appendix C.

3.2. System analysis

This section discusses tugboat production as a system, explored with a black box analysis and a CAT-WOE analysis.

3.2.1. Black box analyis

The tugboat production system aims to transform raw materials and components into tugboats. This system can be seen as a black box (Figure 3.1) and is bound by requirements and outputs several performance indicators.

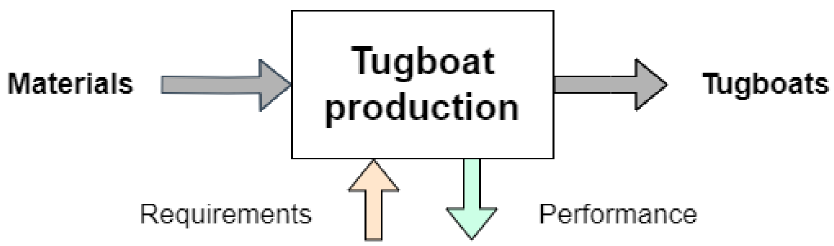

Figure 3.1: General overview of the black box model

Inputs and outputs

The system's inputs and outputs revolve around its transformation; material goes into the system and is converted into completed tugboats.

Requirements

The requirements that bound the system are the customer orders that drive the need of the market, the specifications made by the designers and engineers, and the capacity of the equipment, labour, and land space.

Customer orders are an important requirement in this system, as these drive the demand for the manufacturers. When a customer order is placed well in time, there is room for customisation on the product, as discussed in Chapter 2. This means the design specifications can be altered at a customer's request.

The design specifications include engineering drawings and each vessel's corresponding Bill of Materials. This design must be completed according to the manufacturing steps specified in the Bill of Operations. When the production system includes a whole portfolio of vessels, the ships must be manufactured according to the yard's broader portfolio planning. This is managed through the MRP system, as discussed in Chapter 2.

The system is also bound to the capacity of the real-world situation, with the four essential requirements: capital, labour, equipment and land-space availability. The capital constraint dictates the limit on investments allocated towards materials, labour costs, and yard space, among other essential resources. Furthermore, the labour constraint outlines the available workforce, influencing the pace and scale of production activities. Additionally, the capacity of machinery and equipment limits the volume and complexity of production processes that can be undertaken simultaneously. Lastly, yard, land, and quayspace availability constrains the physical footprint within which production operations can be conducted.

Performance

The production system's key performance indicators (KPIs) are essential for assessing the efficiency, quality, and overall performance of tugboat production. The KPIs can be divided into production efficiency, cost management and operational performance.

Production efficiency is measured by production yield, manufacturing lead time, capacity utilisation, labour productivity and material waste. Production yield is a fundamental measure of productivity, indicating the total number of vessels produced within a specified timeframe. Manufacturing lead time reflects the average duration required to complete the manufacturing process for a single vessel, from initiation to delivery. Capacity utilisation highlights how labour, machinery, and facilities are effectively employed in production activities. Labour productivity assesses the workforce's efficiency, whereas material waste indicates the extent of resource optimisation.

Cost management is measured in production cost and equipment downtime. Production cost quantifies the average expenditure incurred in manufacturing for each vessel, and equipment downtime measures the time machinery and equipment are not operational.

Operational performance quantifies the quality of operations and is measured in yield rate, customer satisfaction, safety performance, and environmental impact. The yield rate measures the proportion of vessels meeting quality standards; when rework has to be done, the yield rate decreases. Customer satisfaction measures the desires of customers that are met; higher satisfaction levels can increase market competitiveness. Safety is a number one priority in yards all around the world, minimising accidents and operational disturbance. Environmental impact should be minimised as much as possible for a sustainable world.

These KPIs collectively facilitate informed decision-making, continuous improvement, and alignment with organisational objectives.

3.2.2. CATWOE analysis

Understanding the dynamics of any system is fundamental to developing effective strategies and solutions. In the context of tugboat production, a CATWOE analysis provides invaluable insights into the various stakeholders, processes, and considerations shaping the industry's landscape. This analysis covers the system's Customers, Actors, Transformation, Weltanschauung (Worldview), Owner, and Environment.

Customers: The system's customers are governments, yards, and shipping companies worldwide. They desire high-quality vessels with swift delivery times and a low price tag. In recent years, the demand for green solutions to operate with low- to zero-emission vessels has been rising.

Actors: The system's actors include shipbuilding companies, yards, suppliers, and transport companies. Designers, engineers, workers, etc., within these companies, all participate in the system's transformation.

Transformation: According to the design specification, the transformation converts raw materials and labour into completed tugboats. This includes the project planning stages: design, production, assembly, testing, and delivery.

World view: The worldview in tugboat production involves safety, reliability, efficiency, and environmental sustainability - especially with zero-emission vessels. Stakeholders may prioritise factors such as meeting client needs, adhering to industry standards, and minimising the environmental impact of production processes.

Owner: Owners of tugboat production are the shipbuilding companies overseeing the production process, including decision-making, resource allocation, and risk management. Other stakeholders could include investors, shareholders, or government entities interested in the production operation's success.

Environment: Environmental constraints in tugboat production include regulatory requirements related to emissions, waste disposal, and hazardous materials. Economic factors, market demand, technological limitations, and geopolitical considerations may influence production.

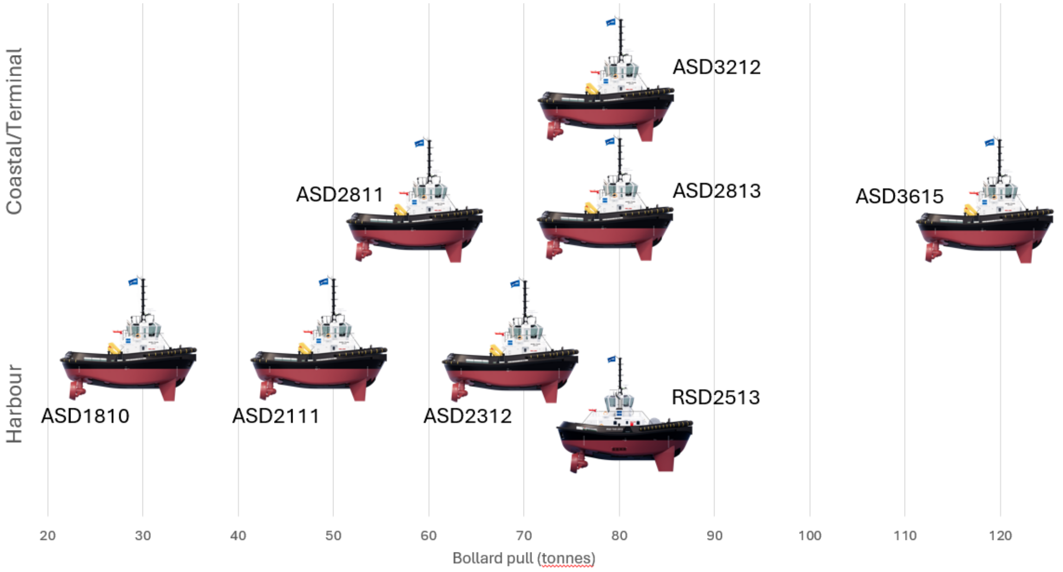

Figure 3.2: Damen's tugboat portfolio. (Damen, 2024)

3.3. Damen tug portfolio

Damen's offers a diverse portfolio of tugboats (Figure 3.2) to clients in the maritime industry worldwide and is famous due to its philosophy of standardisation, quality and innovation. Tugboats are designed to operate in coastal and terminal waters or harbours. Within Damen, the tugboats are among the most standardised vessels and can be classified into three product families: Azimuth Stern Drive (ASD) and Reversed Stern Drive (RSD) tugs.

The ASD tug is compact, manoeuvrable, powerful, and cost-effective. It is most used for handling container and bulk carriers in harbours, terminals, and coastal waters. The bollard pull (towline force) ranges from 30 to 120 tonnes. The RSD tug is the reversed variant, produced on the same platform and operating as effectively as the ASD tug. The RSD tug is available with 80 tonnes of bollard pull. Both variants are available in electric and zero-emission variants, with options such as a firefighting system, an oil pollution control system, extra winches and a high-tensile steel variant (ICE class).

Both vessel variants are engineered with standard parts within the platform, and product names are based on variant, length and width. The most standardised options are presented in Table 3.1; these are the options considered in this research.

Product	Standard parts	Percentage of total parts
ASD 2813	xx	57
ASD 2811	xx	52
RSD 2513	xx	52
ASD 3212	xx	52
ASD 2312	xx	51

Table 3.1: The most standardised tugs types within Damen's portfolio, manufactured at DSCS. (Damen, 2024)

Damen manufactures its tugs at several different yards worldwide, with the main yard being Damen Song Cam Shipyard (DSCS). DSCS is a joint venture between Damen Shipyards Gorinchem (DSGo) and Song Cam, a Vietnamese shipyard in Haiphong. The manufacturing process is split into two parts: Song Cam is responsible for delivering the hull for each project, and DSCS is accountable for the remaining construction activities. Song Cam is considered the "Hull Yard" and DSCS is the "Outfitting Yard". The manufacturing process details are discussed in section 3.4.

3.4. Tugboat production

This section is based on company interviews and previous research at Damen by Reiff (2016). Additionally, a swimlane diagram for the tugboat production at Damen is presented in Figure C.1 in Appendix C. The process of tugboat production is roughly the same as the variant of Rose and Coenen (2016) as shown 2.2.3 and the general manufacturing steps are:

1. Hull fabrication
2. Outfitting
3. Painting
4. Commissioning & sea trials (C&ST)

The production of each tugboat is handled as a project and is done based on a standard planning template for each product. Figure 3.3 shows an example of the complete timeline with milestones. When the project timeline is final, the Unrestricted Actions List (UAL) is released; this means that the tug specifications are final and preparations can start, such as final engineering design and procurement. The start steel cutting (SSC) milestone marks the production started.

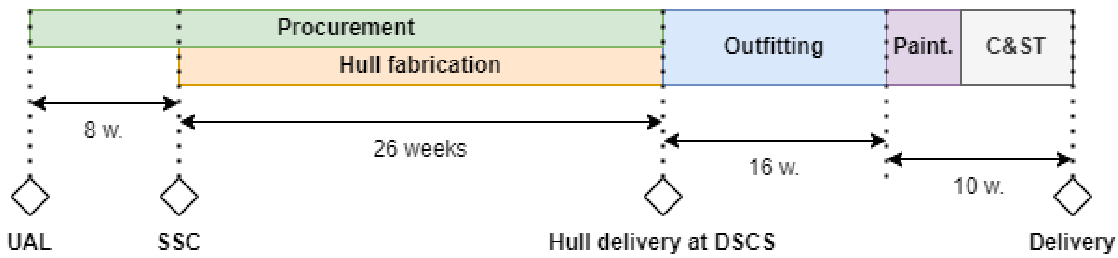

Figure 3.3: Example project timeline with average expected durations in weeks and milestones.

3.4.1. Hull fabrication

The hull fabrication is carried out by the Song Cam Hull Yard and is divided into three main phases: steel cutting (SC), section building and hull assembly. The total production lead time of the hull fabrication is roughly half a year, or 26 weeks. The work breakdown structure for the hull fabrication can be seen in Figure 3.4.

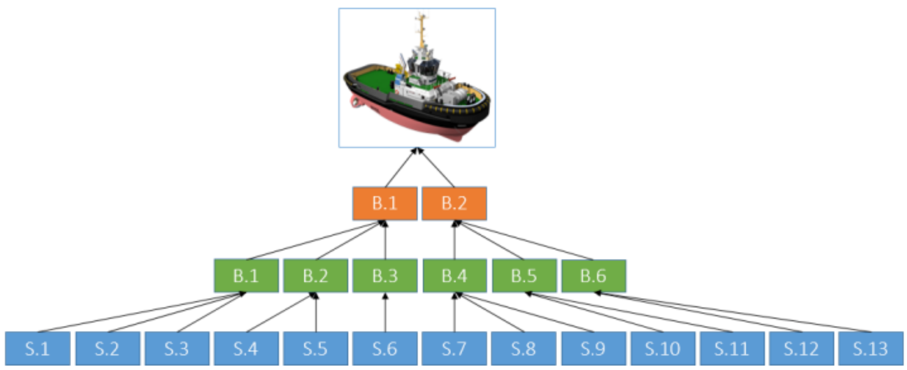

Figure 3.4: The Work Breakdown Structure of the production of tugs. (Reiff, 2016)

After the SSC milestone, steel is cut into plates, ready for the next phase of building the sections. In the section phase, piping and other larger outfitting activities are done parallel on the different sections.

These section units are assembled into block units, as shown in Figure 3.5. The block units are assembled in the final phase to form the hull. (Reiff, 2016) After the hull assembly phase is completed, the hull is delivered to the DSCS yard to start the outfitting phase.

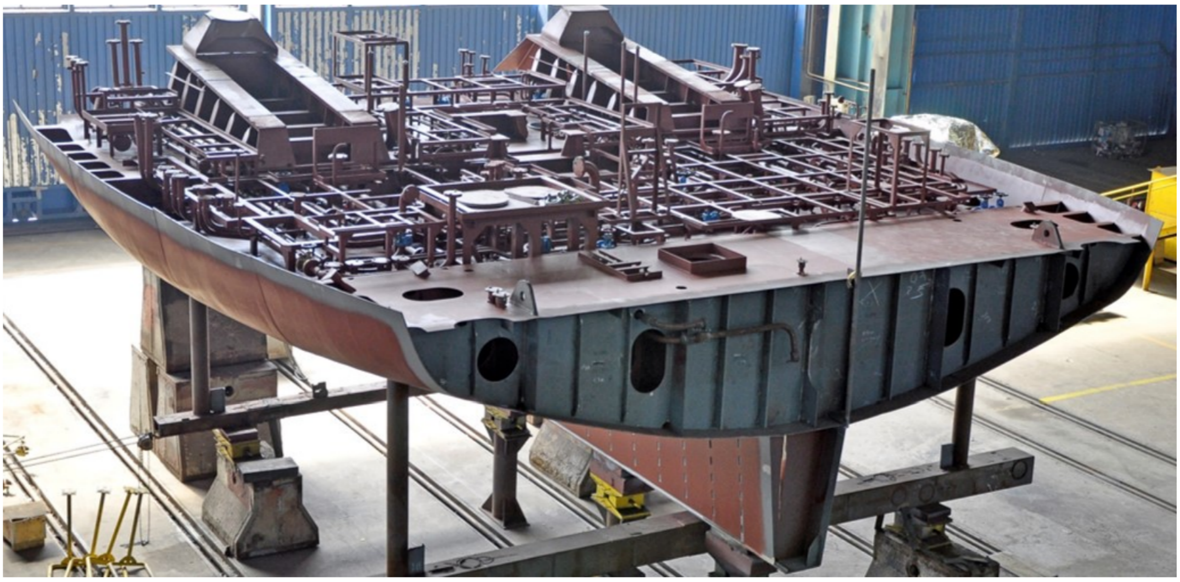

Figure 3.5: A pre-produced hull block. (Reiff, 2016)

3.4.2. Outfitting

In the outfitting phase, a significant portion of the total material value is added to the production process and is around 16 weeks long. This is done in consecutive shop orders. A shop order is a list of work and materials for each activity. It is a loop cycle process where parts are picked from inventory and assembled onto the vessel, and continues to the next shop order.

As the hull fabrication phase was a pyramid-formed structure of assembled parts, the outfitting activities are done in three separate zones: the engine room and steering gear, the accommodation and wheelhouse, and the outside of the hull. The work is performed in parallel to ensure a production timeline of 16 weeks. Notable activities include fitting thruster systems, main engine sets, propellers, towing winches, and generator sets, as these systems have high material value. These activities are given extra attention in case the project planning deviates.

3.4.3. Painting, commissioning and sea trails

After the ship leaves the outfitting hall, it is transported to the paint shop. After painting, the final commissioning is done, and systems are tested according to the operation requirements. Finally, the ship embarks to sea for the last trials on open waters.

3.4.4. Production configurations

The current configuration is making ships to stock - the MTS configuration described in Chapter 2.2. Next to this, there is a possibility for customers to be involved earlier in the production process. This has proponents for both parties in the transaction. In this situation, the client must make several down payments throughout the project timeline for more room for customisation, which reduces manufacturer investment costs for that specific project. However, this dynamic strategy does not mitigate the overall risk of obsolete end products.

This risk mitigation can be tackled by implementing the ATO configuration into the manufacturing process of tugs. This research focuses on the strategic placement of the CODP when implementing the ATO configuration presented by Reiff (2016). According to Reiff (2016), an ATO production configuration for tugs can reduce assembly time and costs.

Figure 3.6 presents three alternative configurations for the shipbuilding production configuration. The CODP can be placed after hull delivery at DSCS - labeled as Outfit to Order. This configuration can be realised with several hulls from different vessel types in stock. The other option is to place the CODP before the hull assembly phase begins. This means that block units are shelved until the client order is final. The last option is to implement the MTO configuration and place the CODP before all production steps.

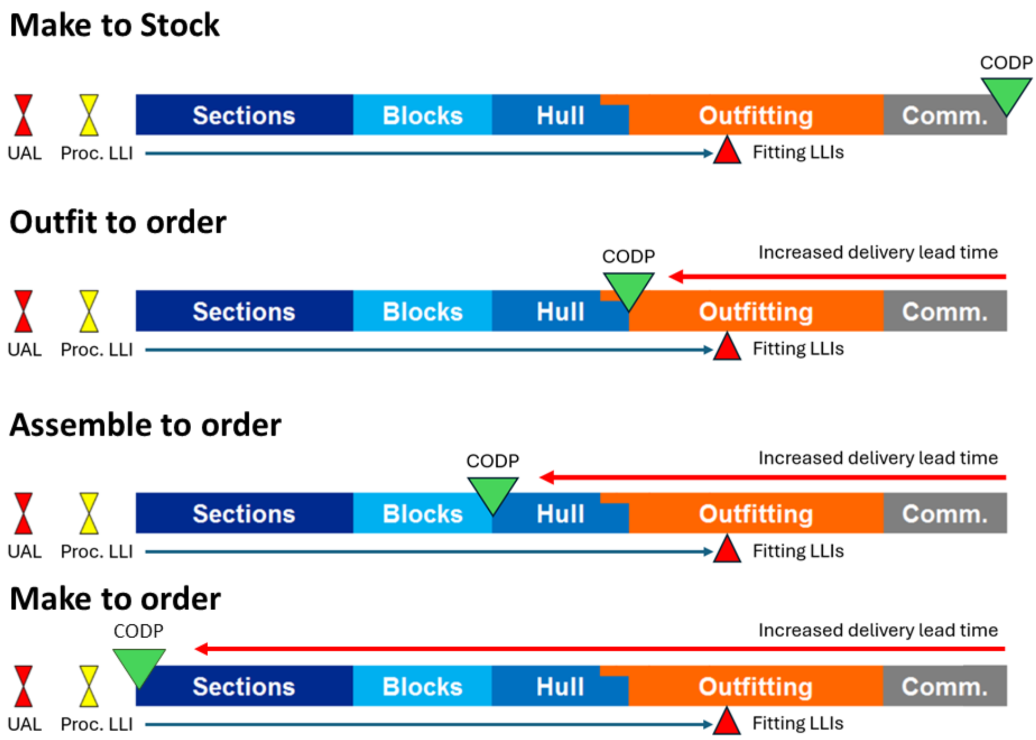

Figure 3.6: The current and three alternative production configurations. (Reiff, 2016)

A notable relationship shown in the figure is the procurement of material, displayed as a yellow sandglass - procurement of long lead items (LLIs). This is when LLIs such as thrusters, generator sets and engines have to be ordered due to their long supply lead time; then at the red triangles in the timeline, these LLIs are fitted onto the vessel.

When the ATO production configuration is applied, it can be seen that the CODP is now at an earlier moment than the fitting moment of LLIs. This means that some components have to be put on stock, same as block units or hulls, otherwise the project cannot start because it has to wait for these parts. As discussed in Chapter 2.2, the BOMO can be analysed to determine when value is added to the production process. If all the supply and transport lead times are known, which items are LLIs and have to be stocked and the stock's material value can be calculated.

If the CODP placement date is considered as T_{CODP}, the fitting date of a part as $T_{fitting}$ and the supply and transport lead times as $LT_{procurement}$ and $LT_{transport}$; then the stock items can be defined as all the parts where the following formula is true:

$$T_{CODP} < T_{fitting} - LT_{procurement} - LT_{transport}$$

3.5. Data structure

Based on the company and data analysis provided in the interviews (Appendix C), the data at Damen related to this research is available from the ERP system and the planning software. The data and relevant decisions for exclusion are discussed in this section.

The ERP system can generate several different datasets, which are important for the calculation of material value and lead time calculations. The data cannot be exported into one dataset because the ERP environment is separated based on location and department for security purposes. The separate datasets are the BOM, supplier data, historic order data and planning data.

3.5.1. BOM

The BOM is available in two forms, the template BOM (TBOM) or yardnumber BOM (YNBOM). The structure of the BOMs is similar, but the usability of the datasets is significantly different.

The TBOM contains all the possible items in the tug type, thus including all option. The amount of standardised items in the TBOM is around 95%, and the remaining 5% are mostly options. When the project details are final, the only chosen options are transferred to the YNBOM. Each part in the YNBOM is assigned an "Activity ID", which links the part to the planning data. This means that the TBOM is only 95% linked to the planning data. Considering this, the YNBOM data is more reliable for analysis.

The BOM is a dataset of around ten thousand parts, either buy, make or phantom parts, non-physical parts that are used to structure the hierarchy of the BOM. The relevant parameters are presented in Table 3.2.

Parameter	Description
Part No	Unique part number
Part description	Description of the part
MPL Required	Amount of that part needed
Provide Code	Indicate if the part is bought, made or a phantom part
Std planned item	Indicates if the part is standard or optional
Sub Project/Activity ID	Assigned Sub Project number and Activity ID
Inherited Sub Project/Activity ID	Inherited Sub Project number and Activity ID from parent part

Table 3.2: BOM data parameters, as presented in Appendix C.

3.5.2. Supplier data

The supplier data is available from the procurement division in the ERP system and contains all the data provided by the suppliers. As DSGo and DSCS are two different ERP environments, both datasets must be exported but have the same structure. Table 3.3 presents the relevant parameters and descriptions.

Parameter	Description
Part No	Unique part number
Part description	Description of the part
Supplier name	Name of the supplier
Supplier Manufacturing Leadtime	Lead time from order moment to delivery at site
Primary supplier	Indicates the primary supplier for this part number
Price/Curr	Unconverted price per currency as ”Currency” parameter
Currency	The currency in which the ”Price/Curr” is stated
Price Conversion Factor	Conversion factor if supplied in packages
Discount	Supplier discount rate in percentage

Table 3.3: Supplier data parameters, as presented in Appendix C.

The importance of the separation hides in the procurement dynamic between DSGo and DSCS. The DSCS dataset has two sorts of suppliers: local suppliers and DSGo. The DSCS dataset is leading for all parts where DSGo is not the primary supplier. For all other parts, the DSGo dataset is to be used. If only one database is used, data is either incorrect or missing.

3.5.3. Order data

As presented in Appendix C, parts are delivered via the DSGo warehouse or directly to the DSCS yard. This data can be retrieved from the historical procurement data, which describes the delivery address for each part (Table 3.4). This is essential in determining the total lead time because the Supplier Manufacturing Leadtime in the supplier data depends on the delivery address. If the part is delivered at DSGo, both the DSGo warehouse lead time and the transport lead time must be included in the total lead time calculation.

Parameter	Description
Part No	Unique part number
Delivery Address	Location at which the part is to be delivered

Table 3.4: Historic order data parameters, as presented in Appendix C.

3.5.4. Planning data

This data is available from the planning software and contains template planning structures, which is copied every time a new project is being planned. Each project has a desired delivery date, the template planning is aligned with that date and the project planning is determined.

The planning software can output Gantt charts and current and template project timelines. The timelines are structured as follows: each activity has a start and end date and is related to the ERP system through an activity ID. Using this data, each part can be linked to a specific date. The parameters are shown in Table 3.5.

Parameter	Description
Activity ID	Activity identifier
Start date	Start date of the activity in dd/mm/yyyy
End date	End date of the activity in dd/mm/yyyy

Table 3.5: Historic order data parameters, as presented in Appendix C.

3.6. Conclusion

Thus, the tugboat production system is analysed using a black box and CATWOE analysis, followed by a case-specific analysis of tugboat production at Damen. Production can be split into several phases, the most critical being hull fabrication and outfitting due to their time length, labour intensity and material value added. The ATO configuration can be implemented by shifting the CODP earlier onto the production timeline, resulting in a relationship between material value and delivery lead time. Finally, the data available at the company is presented, the most important being the BOMs, supplier data, historical order data and template planning. This answers the third research question:

> *What are the key aspects of Damen's tugboat production and which data is available?*

4 Modelling

4.1. Introduction

This chapter will bridge the knowledge discussed in Chapters 2 and 3 to develop a mathematical model to answer the following research question:

How can the tugboat production be modelled, and what are the key data elements?

This will be answered in two steps: firstly, a conceptual model is presented, drawing from the insights gained in the previous chapters. This three-step conceptual model is a foundation for the subsequent step, where a proposed model is presented. This proposed model builds upon the conceptual framework developed and the data presented in Chapter 3. At last, the three steps are shown in sequence in the final model.

4.2. Conceptual model

4.2.1. Scope

The conceptual model is constructed based on the literature discussed in Chapter 2, the system analysis and available company data as presented in Chapter 3. This section outlines the derivations from the previous chapters and the assumptions made. The tugboat production system is discussed as a system where materials flow inwards, and tugboats flow outwards. With a focus on material procurement and investment risk, this system can be adapted as shown in Figure 4.1. The inputs and outputs are discussed in the following section.

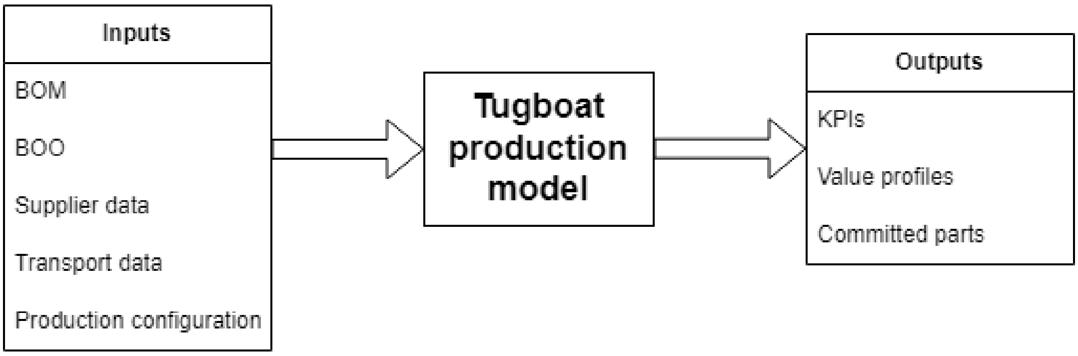

Figure 4.1: The process flowchart for the conceptual model.

4.2.2. Inputs and outputs

To be able to calculate exposure to investment risk, the following data is needed: the BOM, BOO, supplier data, transport data and production configuration. The characteristics of the inputs and outputs are shown in Table 4.1.

Input	Characteristic
BOM	Lists all materials and amounts needed to build a tugboat, along with the activity in which each part is used in the production process.
BOO	Lists the activities and the planned start date of each activity.
Supplier data	Lists the supplier-specified data for each part, such as price, currency, discount and conversion rate and manufacturing lead time.
Transport data	This specifies the delivery location of parts and influences the expected transport time.
Configuration	Specifies which production configurations to calculate.

Table 4.1: Inputs of the model

4.2.3. Outputs

KPIs

The main performance indicator for the customer is **delivery lead time**, as discussed in Chapter 2. In this model, the delivery lead time is considered the number of days between the CODP and the vessel's delivery date. Losses in customisation and the value the customer places on shorter delivery lead times are not considered.

In global financial terms, the **risk exposure** is the monetary evaluation of the risk of losing investments across a stock portfolio or in case of a creditor default. (Gregory, 2009, Malz, 2011) When scoped on a single product or investment, risk exposure reflects the potential loss if the invested product fails to generate returns. Regarding project investment, this is an accumulation of the costs invested into the project over time. In the case of an investment in a vessel, when an MTS configuration is used and a vessel is not sold, the risk exposure equals the total value of the vessel. On the other hand, in an ATO configuration, the risk exposure is lower due to less material commitment to the project.

Daily financing costs refer to the nominal financial costs associated with product financing. (Stone, 1972) It includes interest payments accrued on invested capital each day. For example, if a product is completed but remains unsold, the daily expenses include the interest accumulated over the period it remains shelved awaiting a customer order.

Total financing costs is the sum of daily financial costs accumulated from the start of the project to the CODP, varying according to the selected configuration.

Value profiles

The value profiles are a graphical representation of the risk exposure, daily and total financing cost. These are plotted over the total project time. This time evaluation can later be tied to the increase in delivery lead time.

Committed parts

To determine the parts that make up the total investment amount, the model must generate a list of these components. This list should include all necessary parts that are either already available at the yard or must be procured to ensure that delivery schedules are met.

4.3. Proposed model

Based on the presented literature and company analysis, a relationship exists between delivery lead time and material value used in production, which relates to risk exposure and investment cost. The relationship can be quantified using a BOMO, a tool that consolidates material costs, required units, and associated lead times within a single interface. By generating the BOMO initially, we have the necessary data readily available for analysis. However, the provided data are raw exports from the ERP system, which must be filtered and enhanced before processing the BOMO interface. Figure 4.2 visually represents this three-step process.

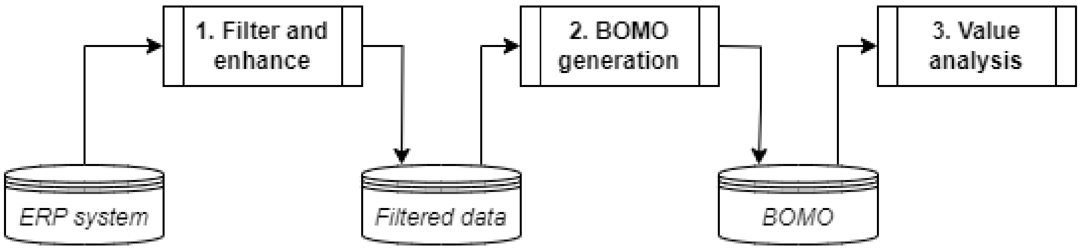

Figure 4.2: Three-step process.

The relevant aspects of Damen's tugboat production to be able to create the BOMO interface are the BOM, BOO, and Supplier data. In addition, transport and warehousing times have to be considered, as predetermined parts are shipped via DSGo. It is assumed that the data provided by the ERP system is leading; if it is not documented in the data, it will not happen. To highlight the scope of the model and show how the BOMO tool can be used, a swimlane analysis for the tugboat production system (Figure 4.3) is based on a simplified version of the swimlane diagram in Figure C.1 in Appendix C.

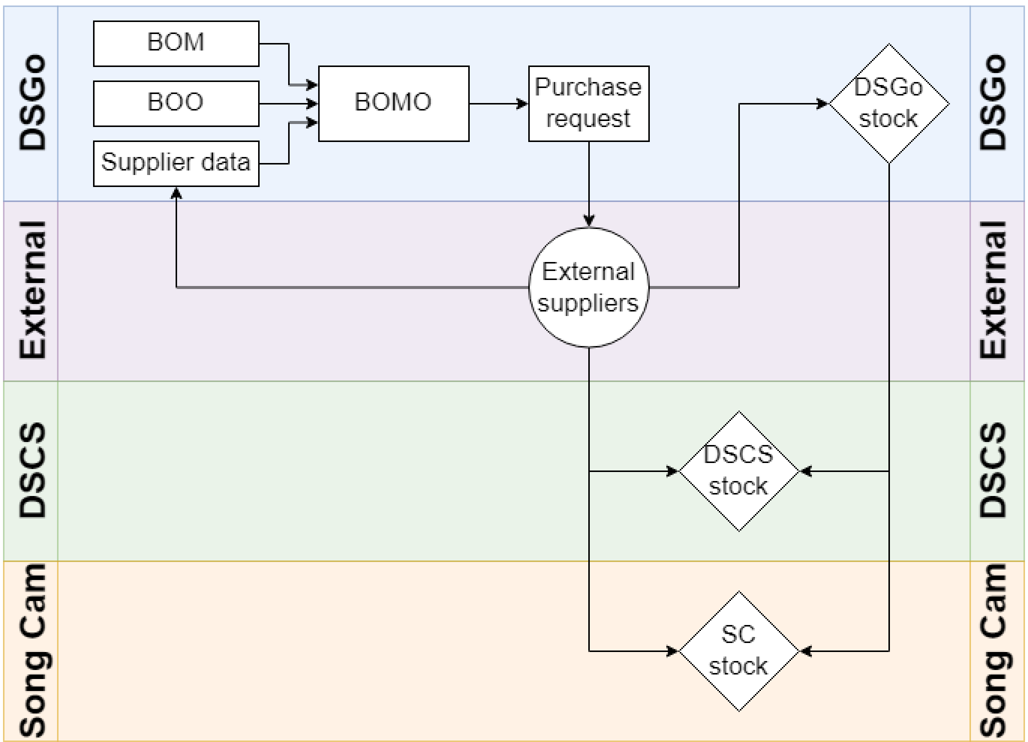

Figure 4.3: Swimlane analysis of Damen's tugboat production, scoped on the BOMO.

4.3.1. Filtering and enhancing

Some filtering and enhancement steps must be implemented before the data is processed. The data from the BOM has to be filtered based on if the part is needed for the BOMO and the activity notation has to be split into sub-project ID and activity ID.

The parts have a "Sub Project/Activity ID" parameter specifying when the part is needed in the production process. When a part does not have that specified, "Inherited Sub Project/Activity ID" can be used, which specifies the parent part's activity data. These values are stored in the SP_p and Act_p parameters in the BOMO. The inputs and outputs are specified in Table 4.2.

Input parameter	Output par.	Raw input	Output	Comment
Part number	P_p	1396037	1396037	No filtering
Part description	PD_p	Propulsion eng...	Propulsion eng...	No filtering
MPL Required	A_p	1	1	Parts with zero MPL are removed, as these parts are not bought
Sub Project/ Activity ID	SP_p Act_p	5.2.2 / 5.2.2.211A	5.2.2 5.2.2.211A	Splits data and stores in SP_p and Act_p
Inherited Sub Project/Act. ID	SP_p Act_p	5.2.2 / 5.2.2.211A	5.2.2 5.2.2.211A	Takes parent part data, stores in SP_p and Act_p

Table 4.2: BOM data filtering

The BOO data does not need filtering, but the input parameters are stored in the output parameters, as shown in Table 4.3. The transport data is shown in Table 4.4. The supplier data is shown in Table 4.5, and two datasets are considered: the data from the DSGo ERP environment and the DSCS environment.

Input parameter	Output parameter
IFS Activity ID	Act_a
Description	$ActD_a$
Start date	AS_a

Table 4.3: BOO data import

Input parameter	Output parameter
Part Number	P_p
Delivery address	Del_p

Table 4.4: Transport data import

Input parameter	Output parameter
Part Number	P_p
Supplier name	S_p
Price/Curr	PpC_p
Currency	$Curr_p$
Price conversion factor	PCF_p
Discount	$Disc_p$
Supplier Manufacturing Lead Time	$SMLT_p$

Table 4.5: Supplier data import

4.3.2. BOMO generation

The BOMO is created by iteratively merging the input databases per part using a lookup function. The process is shown in Fig 4.4.

The loop starts by finding the part's specific supplier data. Because the input data is segregated into several price attributes, it has to be transformed into the price per part in euros. This is done with the help of a callable Currency function that combines the segregated data and returns the preferred parameter.

The second step in the loop is to find the activity tied to the part in the BOO dataset and calculate how many days the part spends on the yard, defined as the Date to Delivery.

The last step is to check where the part is supposed to be delivered, and if it is delivered at DSGo, then the lead times for warehousing and transport from DSGo to DSCS must be considered. Then, the latest possible procurement date is calculated using specified lead times for each part, such as supplier manufacturing lead time, transport time, warehouse times and buffer times.

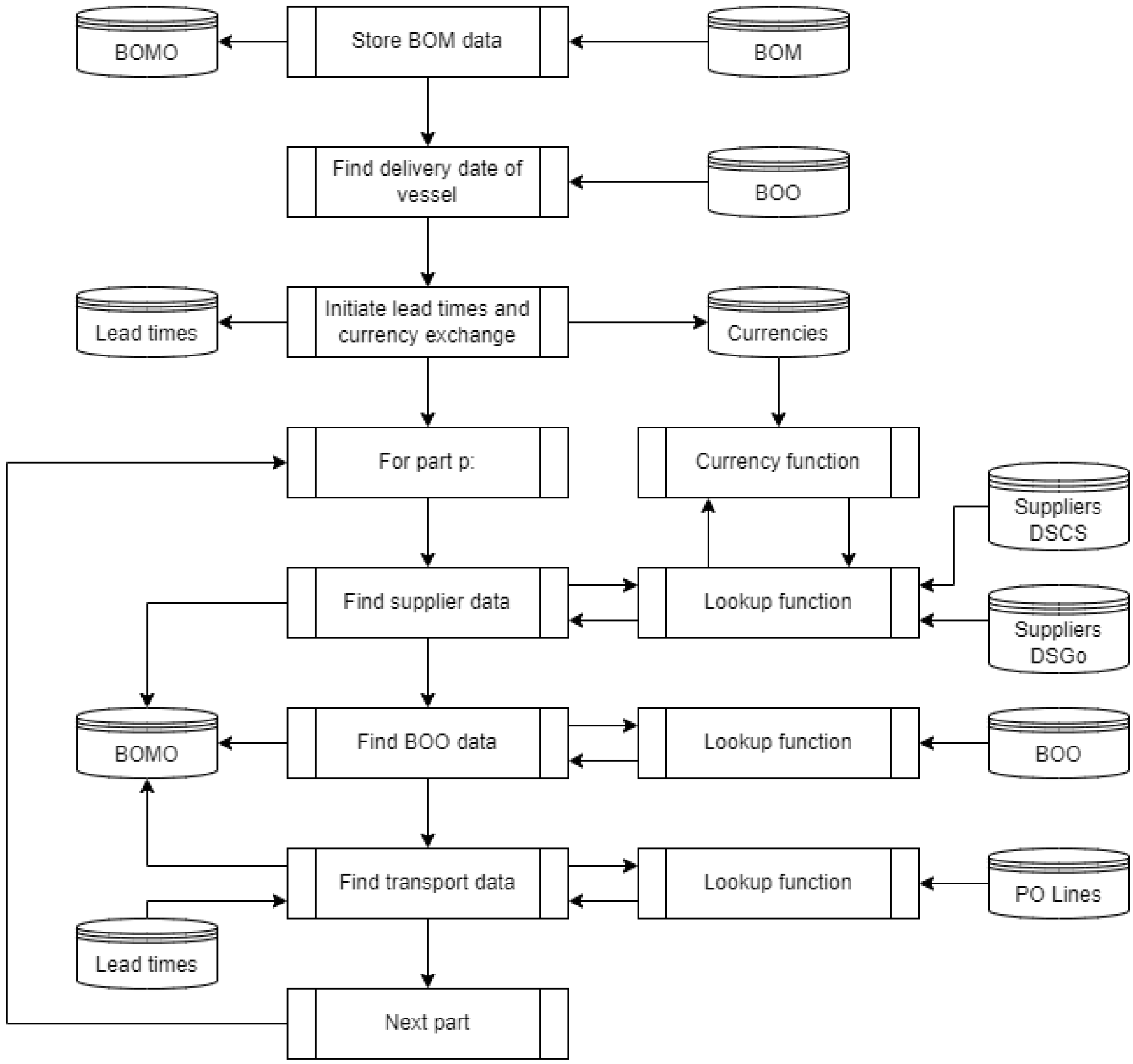

Figure 4.4: Generation of the BOMO

BOMO parameter	Description
P_p	Part number
PD_p	Part description
A_p	Amount of part
SP_p	Subproject ID
Act_p	Activity ID
S_p	Supplier name
PpP_p	Price per part in Euro
AV_p	Added value in Euro
$SMLT_p$	Supplier manufacturing lead time
DTD_p	Days between the date the part is needed on the yard and the delivery of the vessel
$DirD_p$	Binary value: 0 if the part is directly delivered to DSCS, 1 if delivered to DSGo
$PurD_p$	Days between the latest purchase date and the delivery date of the vessel

Table 4.6: BOMO parameters

- Import BOM parameters for all parts
- Find delivery date of vessel in BOO data
- Initiate values for
  - Warehouse time DSGo as $WHTDSGo$
  - Transport time DSGo to DSCS as T
  - Warehouse time DSCS as $WHTDSCS$
  - Buffer time as $BufferDSCS$
  - Currency exchange rates as ExR_{curr}
- For each part P_p:
  - Find supplier data
    - If supplier is DSGo: search part P_p in DSGo SFPP database
    - Else: search part P_p in DSCS SFPP database
    - Return tho BOMO dataset:
      - Supplier name S_p
      - Manufacturing lead time $SMLT_p$
      - Price per part $PpP_p = ExR(Curr_p) * PpC_p * \frac{100-Disc_p}{100} * PCF_p$
      - Added value $AV_p = PpP_p * Ap$
  - Find BOO data
    - If Act_a is not found, or Act_a » $AS(Delivery)$, then $AS_a = AS(Delivery)$
    - Calculate $DTD_p = AS(Delivery) - AS_a$
    - Return DTD_p
  - Find transport data
    - If the delivery address is DSGo: $DirD_p = 1$
    - Else: $DirDp = 0$
    - Calculate purchase date:
      $PurD_p = DTD_p + WHTDSCS + BufferDSCS + DirD_p * (WHTDSGo + T)$
    - Return $PurD_p$

4.3.3. Value analysis

The main goal of the value analysis is to graphically represent the system's KPIs, which are risk exposure, daily financing costs, and total financing costs.

Risk exposure over time is calculated by summating the material costs incurred across different time periods. Within this model, the total material cost associated with each part is denoted as AV_p in the BOMO, while the moment of commitment to purchase the part is indicated by $PurD_p$. A two-dimensional index is created, represented by d for time periods and p for parts, utilising these values. The purchase date is aligned along one axis, while the individual parts are arranged along the other. This indexing approach is shown by Equation 4.1, where CV_{dp} represents the risk exposure for part p at time period d.

$$CV_{dp} = AV_p \times x_d \tag{4.1}$$

Here, x_d is a binary variable defined as follows:

$$x_d = \begin{cases} 1 & \text{if d is } PurD_p \\ 0 & \text{otherwise} \end{cases} \tag{4.2}$$

This equation ensures that CV_{dp} is equal to AV_p only when the time period d corresponds to the purchase date $PurD_p$, and 0 otherwise. Such a representation allows for precise tracking of the risk exposure over time and across different parts of the system. The risk exposure equals the accumulated commitment value over time.

$$EP(t) = \sum_{d=0}^{t} \sum_{p \in P} CV_{dp} \qquad with \qquad 0 < t < length(d) \tag{4.3}$$

The daily financing costs can be found by multiplying the risk exposure EP with the daily interest rate DIR.

$$DFC(t) = EP(t) * DIR \tag{4.4}$$

The total financing costs TFC over time t are the integration of the daily financing cost:

$$TFC(t) = \sum_{i=0}^{t} DFC(i) \tag{4.5}$$

4.3.4. Output

The model's outputs are the value profiles, the KPIs, and the committed parts over time. The value profiles are created by plotting $EP(t)$, $DFC(t)$ and $TFC(t)$ over t. The KPIs and committed parts are dependent on the chosen configuration. These configurations have a placement of the CODP at time t. The KPIs are calculated with $EP(CODP)$, $DFC(CODP)$ and $TFC(CODP)$. The committed parts are dependent on the CODP chosen, these are all the parts with $PurD_p \leq CODP$

4.4. Final model

The three steps of importing, generating the BOMO and performing the value analysis are combined into a final deterministic model, shown in Figure 4.5. The code languages are shown in Appendix D

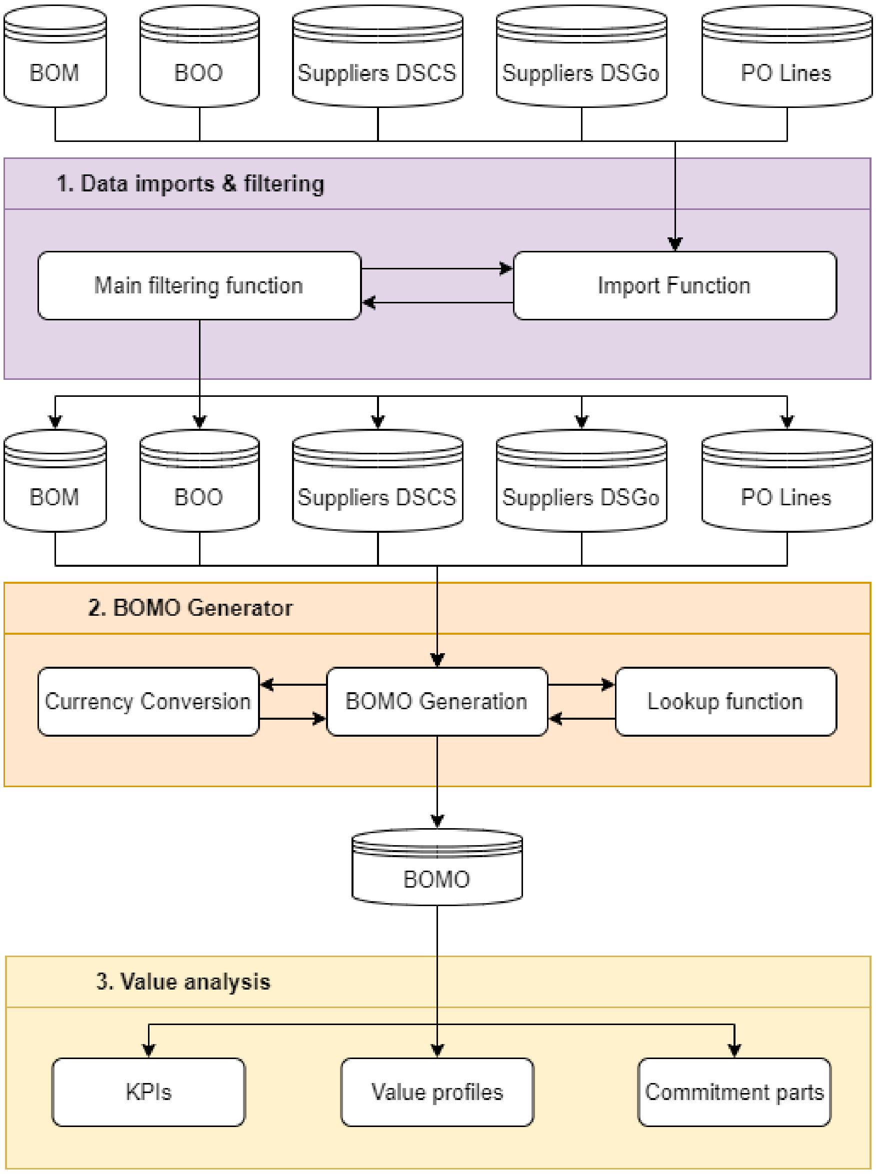

Figure 4.5: The process flowchart for the final model.

4.5. Conclusion

To model the tugboat production focusing on material value and financing costs, a conceptual model is presented as a three-step process consisting of importing and preparing available data, generating a BOMO database, and performing value analysis on the BOMO data.

The inputs of the model are the BOM, BOO, Supplier data and transport data, which are merged to form the BOMO data set. The BOMO generation process is discussed and the mathematics behind the key data elements is shown, followed by a clarification of the value analysis profiles. Finally, the complete process of the three steps model is presented, answering this chapter's research question:

How can the tugboat production be modelled, and what are the key data elements?

5

Model validation

The model presented in Chapter 4 has to be verified and validated before experiments can be conducted. Therefore, this chapter will answer the fourth research question:

How can the model be validated and how does this relate to the standard method to calculate delivery lead time adaption?

First, the context of lead time adaption is discussed, and then the model is verified through scenario testing and parameter tuning.

5.1. Lead time adaption

According to Wouters (1991), lead time reduction has many benefits depending on implementation. In the context of this paper, lead time reduction can be achieved at the delivery side of the supply chain. More specifically, it can be done by shifting the CODP upstream of the supply chain. For this implementation, Wouters (1991) mentions that the customer value of lead time should be analysed critically to quantify the delivery lead time performance metric.

Generally speaking, customers are prepared to pay more for products with shorter delivery lead times. However, this thesis does not indicate how much Damen's customers value delivery lead time. Therefore, the company should make the final decision after thoroughly researching customer needs and preferences.

5.2. Verification

Verifying the model involves assessing whether it accurately represents the intended system and produces outputs as intended. This verification process is conducted through two methods. Firstly, we perform scenario testing, wherein we input a small predefined dataset into the model and assess whether the intermediate and final outputs align with our expectations. Following this, we conduct parameter tuning tests, where we input a specific set of parameters into the model and adjust them to observe if the model behaves as expected.

5.2.1. Scenario testing

BOMO generation

The BOMO generation can be verified by importing five simple databases of predefined parts and corresponding parameters. Table 5.1 shows the imported BOM data, Table 5.2 and 5.3 show the imported supplier data, Table 5.4 shows the imported BOO data and Table 5.5 the imported purchase order line data. The remaining assumptions are presented in 5.6.

P_p	PD_p	A_p	Act_p
1	Part 1	1	1.1
2	Part 2	5	1.1
3	Part 3	10	2.1
4	Part 4	20	2.1
5	Part 5	100	3.1

Table 5.1: BOM data

P_p	PpC_p	$Disc_p$	$Curr_p$	PCF_p	S_p	$SMLT_p$
1	100	0	EUR	1	Supplier A	150
2	50	0	EUR	1	Supplier B	100
3	20	0	EUR	1	Supplier A	30
4	10	0	EUR	1	Supplier B	20
5	5	0	EUR	1	Supplier C	20

Table 5.2: Supplier data DSGo

P_p	PpC_p	$Disc_p$	$Curr_p$	PCF_p	S_p	$SMLT_p$
1	200000	0	VND	1	Supplier A	150
2	100000	0	VND	1	Supplier B	100
3	5	0	EUR	1	Damen Shipyards Gorinchem B.V.	30
4	2	0	EUR	1	Damen Shipyards Gorinchem B.V.	20
5	1	0	EUR	1	Damen Shipyards Gorinchem B.V.	20

Table 5.3: Supplier data DSCS

Act_a	$ActD_a$	AS_a
1.1	Activity 1	0
2.1	Activity 2	100
3.1	Activity 3	200
DEL2ND	Delivery date of vessel	300

Table 5.4: BOO dataset

P_p	Del_p
1	4
2	4
3	4
4	191
5	191

Table 5.5: Purchase order dataset

Parameter	Assumption
$Del_p(DSGo)$	4
$WHTDSGo$	7
T	80
$WHTDSCS$	21
$BufferDSCS$	7

Table 5.6: Model input assumptions

It is expected that the suppliers per part are converted into only Supplier A, B or C and that the price per part is converted into Euro. The DTD of the parts are to be expected as per Table 5.4 and to be converted into days left until delivery. The expectation for transport time is that parts 1, 2 and 3 are not directly delivered, resulting in 87 days of extra transport lead time as opposed to parts 4 and 5. The output of the model into the BOMO dataset is shown in Table 5.7.

P_p	PD_p	A_p	Act_p	S_p	PpP_p	AV_p	$SMLT_p$	DTD_p	$DirD_p$	$PurD_p$
1	Part 1	1	1.1	Supplier A	7,4	7,4	150	300	1	565
2	Part 2	5	1,1	Supplier B	3,7	18,5	100	300	1	515
3	Part 3	10	2,1	Supplier A	20	200	30	200	1	345
4	Part 4	20	2,1	Supplier B	10	200	20	200	0	248
5	Part 5	100	3,1	Supplier C	5	500	20	100	0	148

Table 5.7: Generated BOMO dataset

Value analysis

Based on the $PurD_p$ of the parts, the hypothesis is that the $EP(t)$ profile will step up at the $PurD_p$ for each part, with a step of AV_p for the corresponding part and a maximum of the total value of the five parts: €925,90. Figure 5.1 supports this hypothesis.

Based on Equation 4.4, the $DFC(t)$ profile should be the same as the $EP(t)$ profile multiplied by the daily interest rate, leading to a maximum of €0,127. Figure 5.2 supports this hypothesis.

The total financing costs are the accumulated area under the $DFC(t)$ profile, with the derivative increasing at the same date as the steps of the $DFC(t)$ profile. The total financing costs at the end of the project should equal $DIR \times AV_p \times PurD_p$. For parts 1 - 5, these values are €0,57, €1,21, €9,45, €6,79, €10,14. This leads to a total of €28,26, and Figure 5.3 supports this hypothesis.

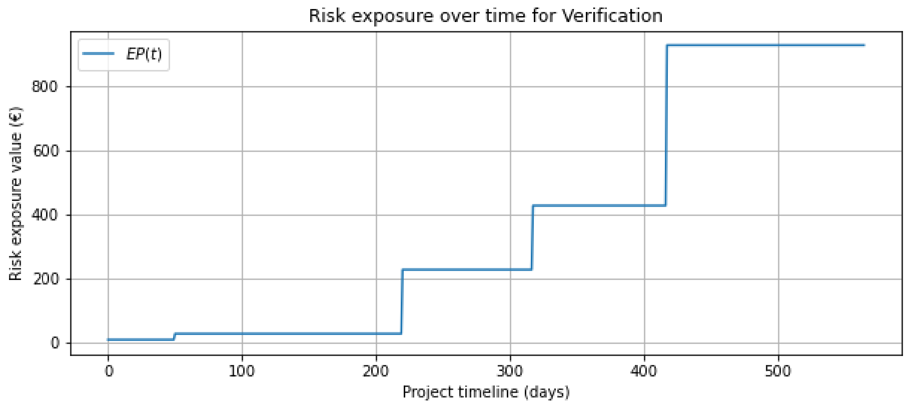

Figure 5.1: Risk exposure over time.

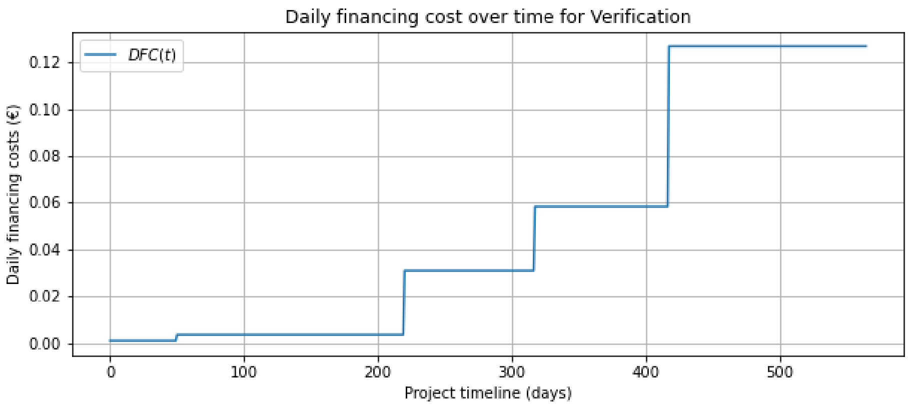

Figure 5.2: Daily financing costs, assuming a yearly interest rate of 5%.

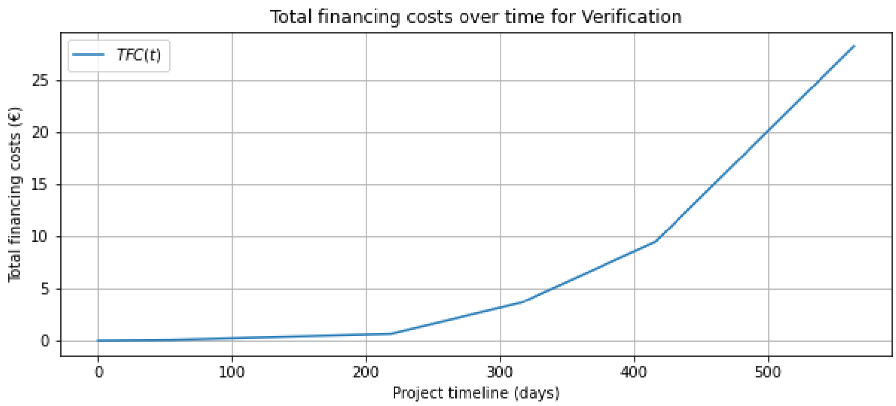

Figure 5.3: Total financing costs, assuming a yearly interest rate of 5%.

5.2.2. Parameter tuning

Cases

Case	Description
1	Baseline input, same input files as Section 5.2.1, only Part 1 of BOM
2	Change activity ID to 2.1
3	Double price per part
4	$SMLT_p = 0$
5	$DirD_p = 0$

Table 5.8: Caption

Hypotheses

Based on the model's inputs, the BOMO data will differ slightly per case. Table 5.9 shows which data is expected to differ.

Case	BOMO hypothesis
1	-
2	Activity 2.1 starts 100 days later, so DTD_p and $DPurD_p$ are 100 days less
3	Double price per part and added value
4	$SMLT_p = 0$ and $DPurD_p$ 150 days less
5	$DirD_p = 0$ and $DPurD_p$ 87 days less

Table 5.9: Caption

The hypotheses for the value KPIs are presented in Table 5.10. Due to shorter lead times and thus overall investment time, the TFC values of cases 2, 4 and 5 are to be lower, proportional to the length of d. Due to the doubled price, all three KPIs of case 4 are expected to double.

Case	length(d)	$EP(length(d))$	$DFC(length(d))$	$TFC(length(d))$
1	565	€7,40	€0,0010	€0,57
2	465	€7,40	€0,0010	€0,47
3	565	€14,80	€0,0020	€1,15
4	415	€7,40	€0,0010	€0,42
5	478	€7,40	€0,0010	€0,48

Table 5.10: KPI Hypotheses

BOMO data

The values of the BOMO database after generation are presented in 5.11. As these values are the same as the hypotheses presented in 5.9, the hypotheses are supported and the BOMO creation step is verified.

Case	P_p	PD_p	A_p	Act_p	S_p	PpP_p	AV_p	$SMLT_p$	DTD_p	$DirD_p$	$PurD_p$	H
1	1	Part 1	1	1.1	Supplier A	7,4	7,4	150	300	1	565	S
2	1	Part 1	1	2.1	Supplier A	7,4	7,4	150	200	1	465	S
3	1	Part 1	1	1.1	Supplier A	14,8	14,8	150	300	1	565	S
4	1	Part 1	1	1.1	Supplier A	7,4	7,4	0	300	1	415	S
5	1	Part 1	1	1.1	Supplier A	7,4	7,4	150	300	0	478	S

Table 5.11: Caption

KPIs

The outputs of the value analysis are presented in 5.12. These values are the same as the hypotheses presented in Table 5.10. The hypotheses are supported, and the KPIs are verified.

Case	length(d)	$EP(length(d))$	$DFC(length(d))$	$TFC(length(d))$	Hypothesis
1	565	€7,40	€0,0010	€0,57	Supported
2	465	€7,40	€0,0010	€0,47	Supported
3	565	€14,80	€0,0020	€1,15	Supported
4	415	€7,40	€0,0010	€0,42	Supported
5	478	€7,40	€0,0010	€0,48	Supported

Table 5.12: KPI Hypothesis

5.3. Validation

The model can be validated by using the baseline configuration of an MTS configuration and comparing it to real-world value data for each vessel.

Material costs	ASD2312	ASD2811	ASD2813	ASD3212	RSD2513
Real total (€)	xx k	xx k	xx k	xx k	xx k
Model total (€)	xx k	xx k	xx k	xx k	xx k
Total r. err. (%)	7.54	7.21	8.55	12.42	3.28
Real Outfitting (€)	xx k	xx k	xx k	xx k	xx k
Model Outfitting (€)	xx k	xx k	xx k	xx k	xx k
Outfitting r. err. (%)	5.79	11.74	9.16	11.94	1.80
Real Hull (€)	xx k	xx k	xx k	xx k	xx k
Model Hull (€)	xx k	xx k	xx k	xx k	xx k
Hull r. err. (%)	13.92	6.22	6.49	14.28	7.62

Table 5.13: Comparison of model output and real-world material costs of each vessel. (Damen, 2024)

The price deviation between the model and the real world can be explained by three main factors: inflation, currency exchange rates, and inaccurate pricing data. The exchange rate from Euro (EUR) to Vietnamese Dong (VND) has been volatile in the last three years, with deviations up to 20%. The second factor is the inflation rate, tied with the third factor: inaccurate pricing. Due to the rise of annual inflation in the Netherlands and Vietnam, materials prices have risen with a maximum deviation of 11%, resulting in higher expected costs than real-world transactions in the last three years. However, changes in price data are not always updated in the ERP system, which leads to additional inaccuracy. Arguing the volatility of these factors, a deviation of 11 % is acceptable.

5.4. Conclusion

How can the model be validated and how does this relate to the standard method to calculate delivery lead time adaption?

This chapter discusses the standard method of lead time adaptation and identifies a misalignment between current knowledge of the problem and the standard calculation method. Despite this, a proposition was introduced on incorporating the standard lead time adaptation method into this thesis.

The verification phase consisted of two distinct tests. Scenario testing demonstrated that the model performed as intended, while parameter tuning confirmed all our hypotheses. Consequently, the model has been successfully verified.

Lastly, the model is subjected to real-world data during the validation phase and compared the outcomes. The model exhibited an average error 7%.

6 Results

6.1. Introduction

Financial risk and commitment play essential roles in tugboat production, primarily due to the high value of the products involved and the lengthy lead times associated with their manufacturing. While minimising financial risk and commitment is desirable, achieving this often comes at the expense of fast product delivery to customers. This chapter discusses the impact of delivery lead time and the strategic positioning of the CODP on financial risks and commitments to address the fifth research question:

What are the costs of delivery lead time adaption for Damen's tugboat production?

To accomplish this, a case-study approach is employed. This introduction outlines the experimentation plan, presents the experimental findings, and draws conclusions based on the analysis of the results.

6.2. Experimentation plan

6.2.1. Objective

The primary objective of the experimentation is to assess the impact of adapting delivery lead time on material costs within the tugboat industry. Specifically, the aim is to analyse how alterations in delivery lead time affect the material cost and procurement commitment, considering various factors such as materials, operations, supplier pricing, and transportation logistics. As stated in section 3.3, the considered tugtypes are the ASD 2312, 2811, 2813 and 3212 and the RSD 2513.

The hypothesis is that increased delivery lead time reduces the material costs that must be stocked when a customer has not ordered a vessel. This hypothesis is tested by using the four configurations presented in Figure 6.1

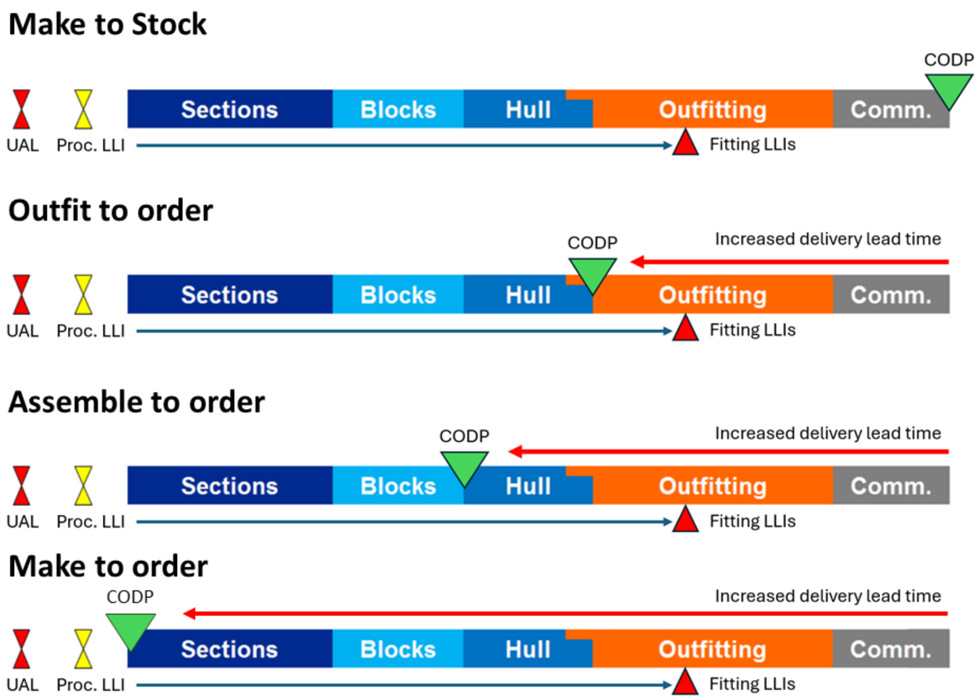

Figure 6.1: The current MTS and alternative production configurations.

6.2.2. Methodology

The experiments use the model presented in Chapter 4. Due to the standardisation within Damen, the experiments can be conducted once per tug type, as each tug is essentially equal.

The experiments' primary variable is based on the three configurations: the delivery lead time, which is the point of interest stated in this chapter's research question. This delivery lead time for each vessel and configuration is shown in Table 6.1. The model outputs the value analysis, the KPIs of the configurations, and a dataset of committed parts for each chosen configuration for each vessel. With five vessels and four configurations, that leads to a total of 20 experiments. Additionally, a weighted average per KPI is presented based on Appendix B.1.

Ship type	MTO	ATO	OTO	MTS
ASD2312	403	293	189	0
ASD2811	385	272	186	0
ASD2813	426	298	206	0
ASD3212	428	293	201	0
RSD2513	385	272	186	0

Table 6.1: Delivery lead time in days for the five ship types and CODP configurations.

An additional set of experiments is conducted based on shortening supplier manufacturing lead time. As mentioned in Chapter 3, the engine, thrusters and generator sets are high-value parts in the tugboat with long supplier lead times. By reducing the $SMLT_p$ of those parts and running the model, the impact of those parts can be seen in the risk exposure and daily financing cost for each configuration. The experiments are run with a reduction of the $SMLT_p$ values of 10%, 20% and 30% and a baseline of 0%.

6.3. Experimentation results

6.3.1. ASD2312 Value analysis

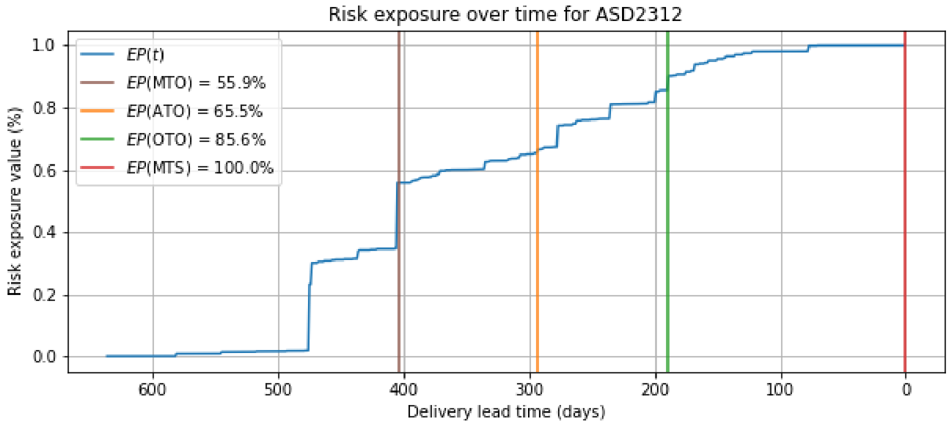

Figure 6.2: Risk exposure over time for an ASD2312.

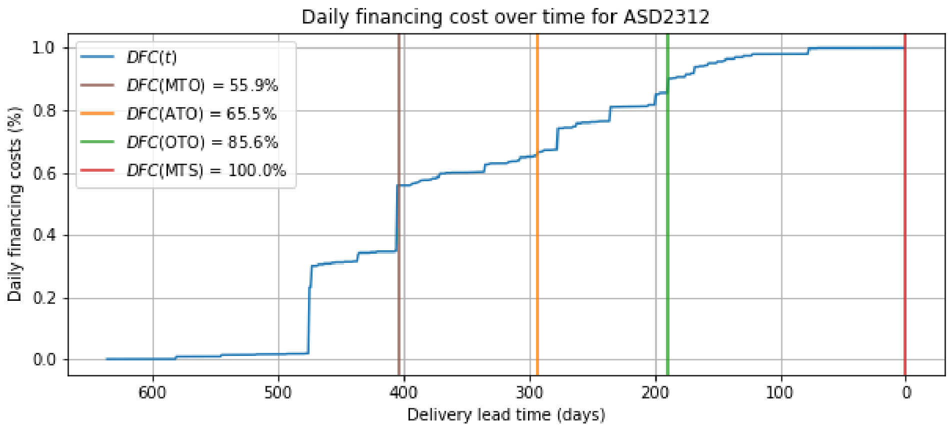

Figure 6.3: Daily financing costs for an ASD2312, assuming a yearly interest rate of 5%.

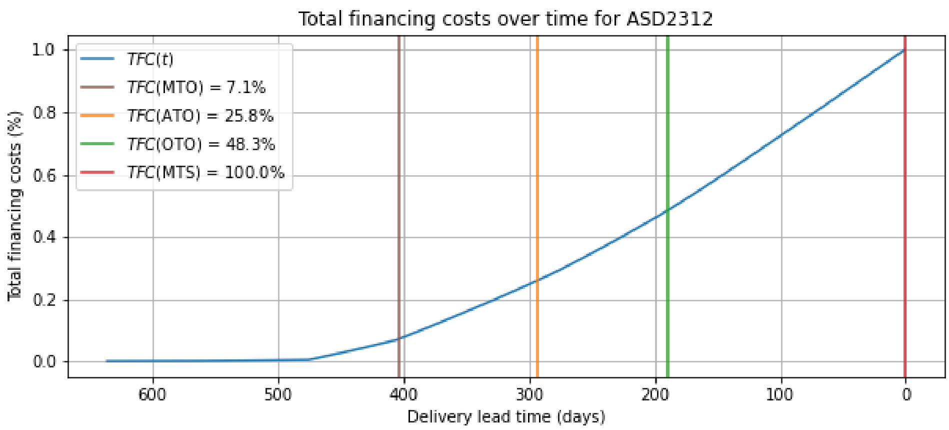

Figure 6.4: Total financing costs of for ASD2312, assuming a yearly interest rate of 5%.

6.3.2. ASD2811 Value analysis

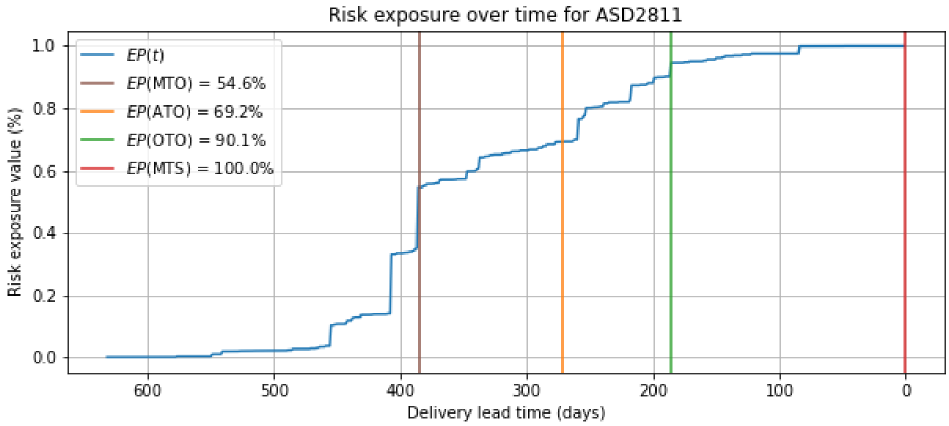

Figure 6.5: Risk exposure over time for an ASD2811.

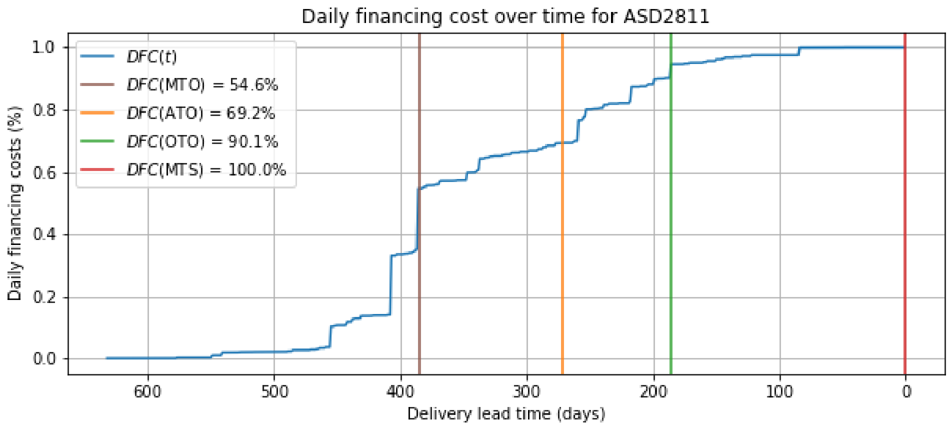

Figure 6.6: Daily financing costs for an ASD2811, assuming a yearly interest rate of 5%.

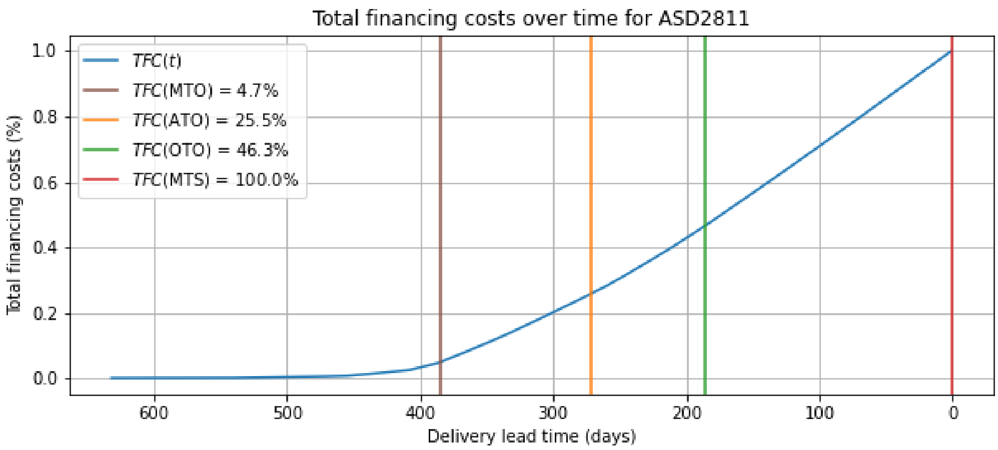

Figure 6.7: Total financing costs of for ASD2811, assuming a yearly interest rate of 5%.

6.3.3. ASD2813 Value analysis

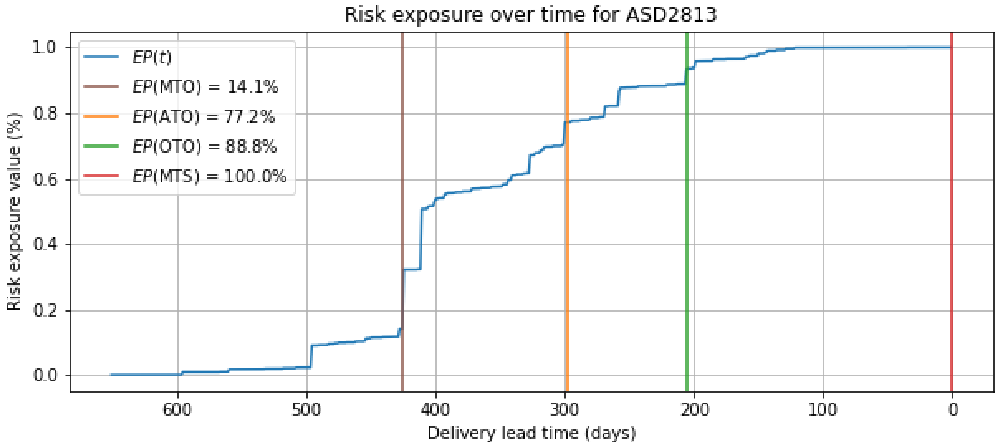

Figure 6.8: Risk exposure over time for an ASD2813.

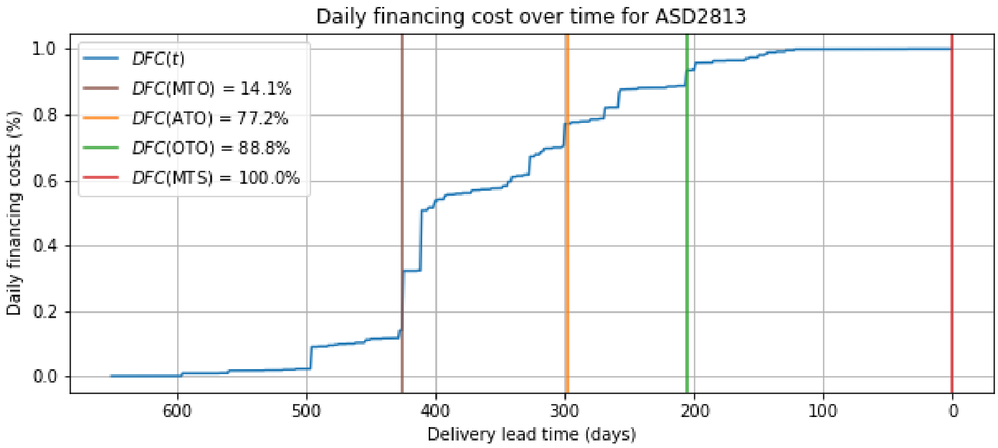

Figure 6.9: Daily financing costs for an ASD2813, assuming a yearly interest rate of 5%.

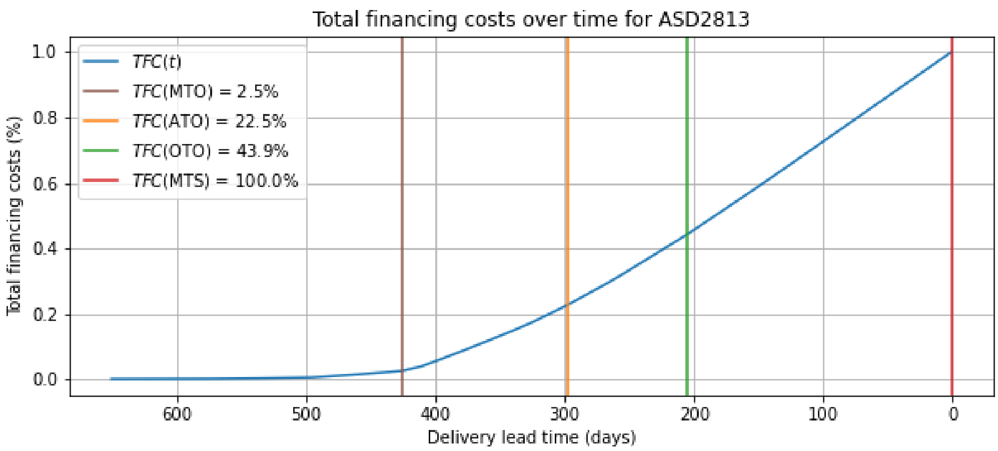

Figure 6.10: Total financing costs of for ASD2813, assuming a yearly interest rate of 5%.

6.3.4. ASD3212 Value analysis

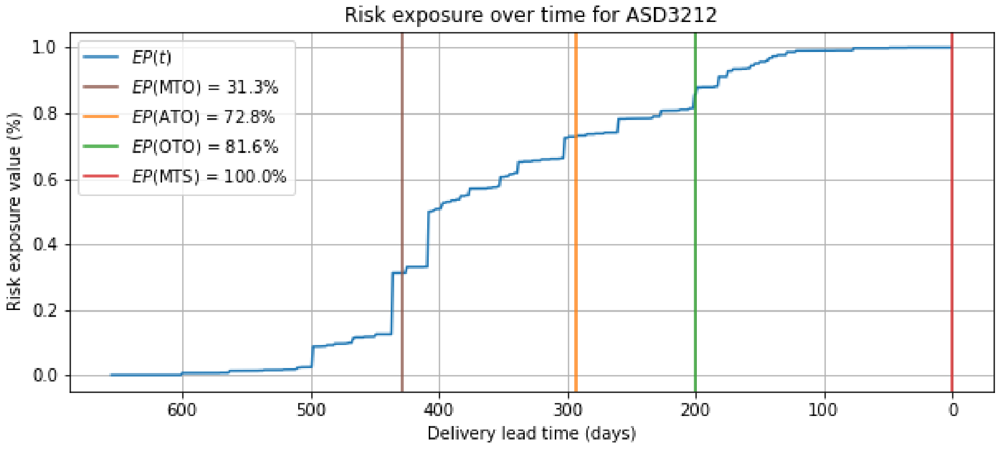

Figure 6.11: Risk exposure over time for an ASD3212.

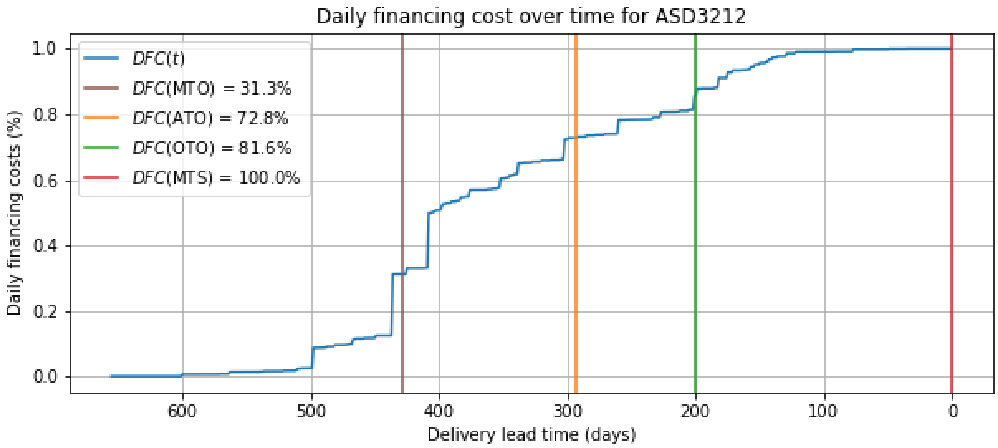

Figure 6.12: Daily financing costs for an ASD3212, assuming a yearly interest rate of 5%.

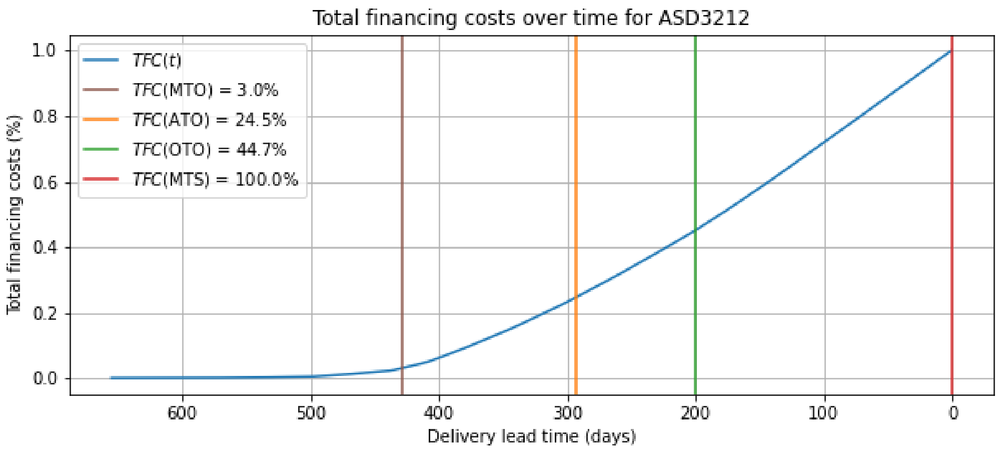

Figure 6.13: Total financing costs of for ASD3212, assuming a yearly interest rate of 5%.

6.3.5. RSD2513 Value analysis

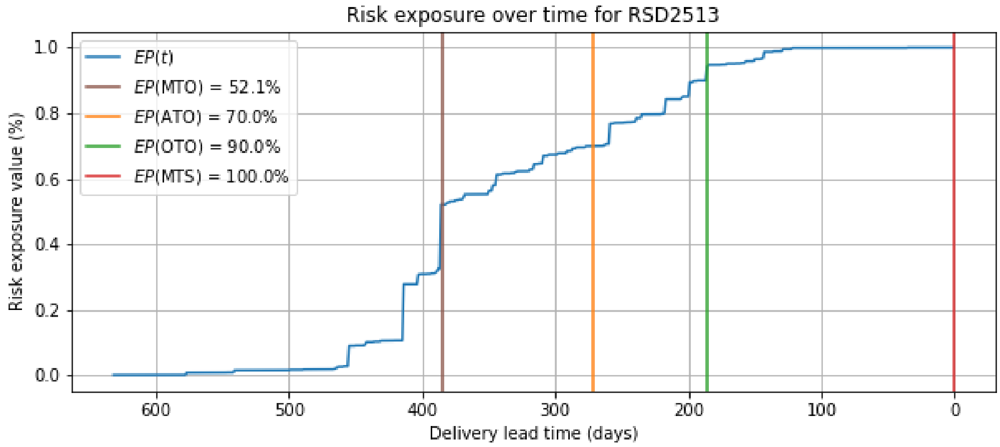

Figure 6.14: Risk exposure over time for an RSD2513.

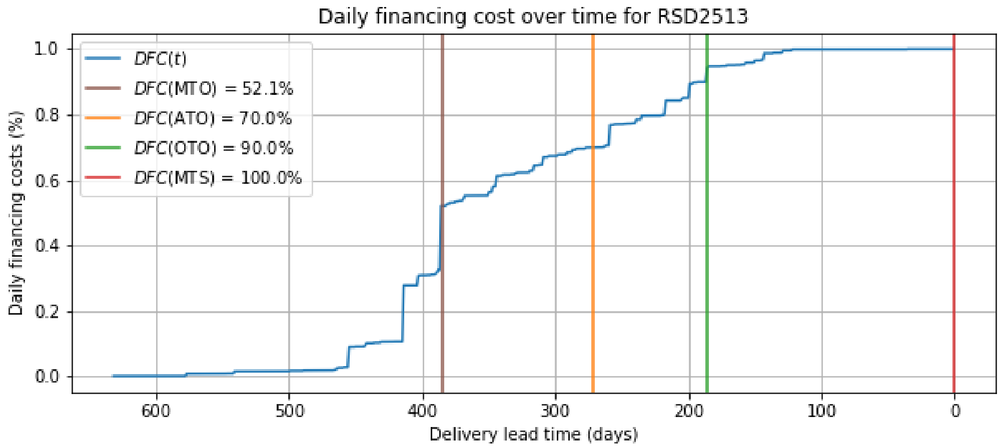

Figure 6.15: Daily financing costs for an RSD2513, assuming a yearly interest rate of 5%.

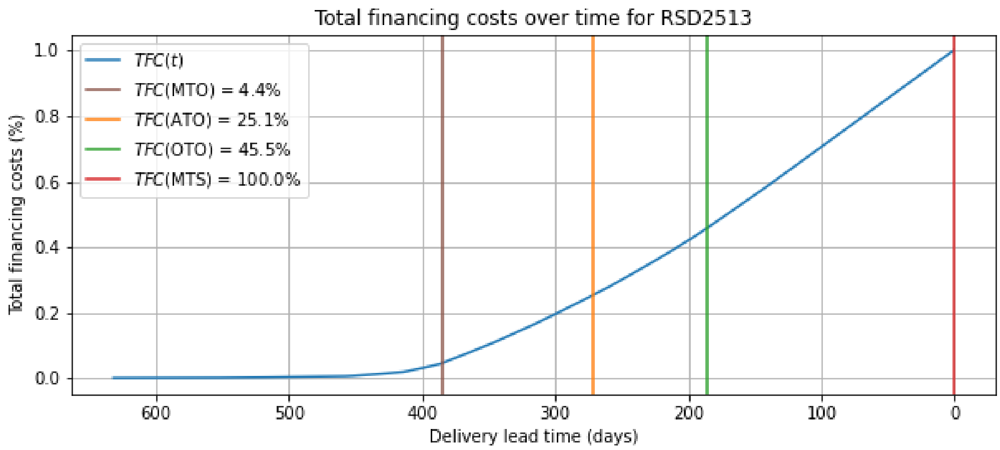

Figure 6.16: Total financing costs of for RSD2513, assuming a yearly interest rate of 5%.

6.3.6. KPIs

The KPIs have been presented in the value plots in percentages due to confidentiality. The absolute and relative KPI values for each ship type are presented in Figures 6.17 - 6.20. It is shown that increasing the delivery lead time for the customer can reduce risk exposure, daily financing costs, and total financing costs significantly. However, it is difficult to determine the best option because it is unknown how much value the customer places on delivery lead time. Therefor, the weighted average based on vessel sales of the past five years have been added, see Table B.1 in the Appendix. (Damen, 2024) Regarding risk mitigation and reducing financing costs, choosing the MTO as the production configuration would be best, especially for the ASD2813 vessel.

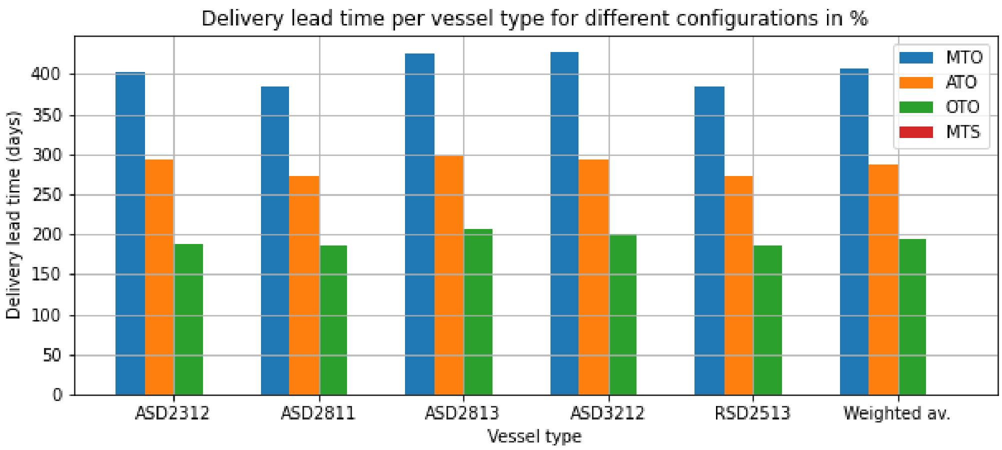

Figure 6.17: Delivery lead time for the five ship types and CODP configurations in percentage project time.

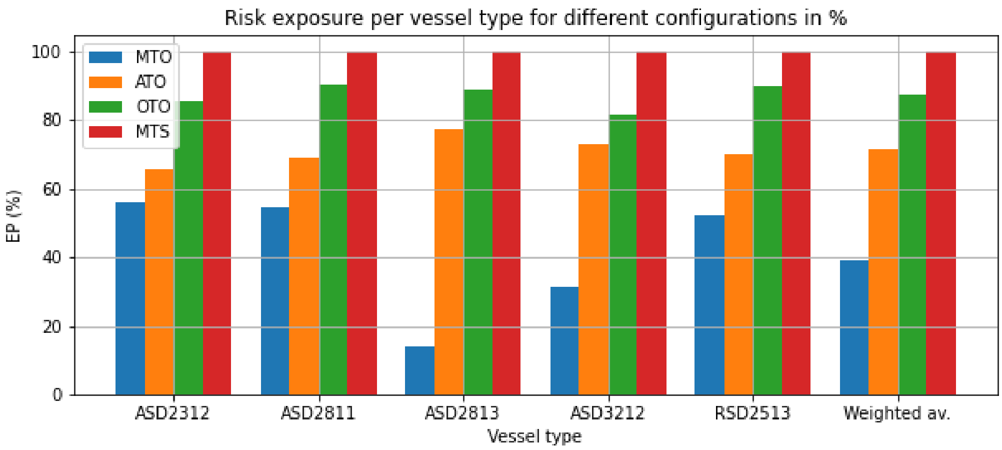

Figure 6.18: Risk exposure for the five ship types and CODP configurations in percentage of total risk exposure.

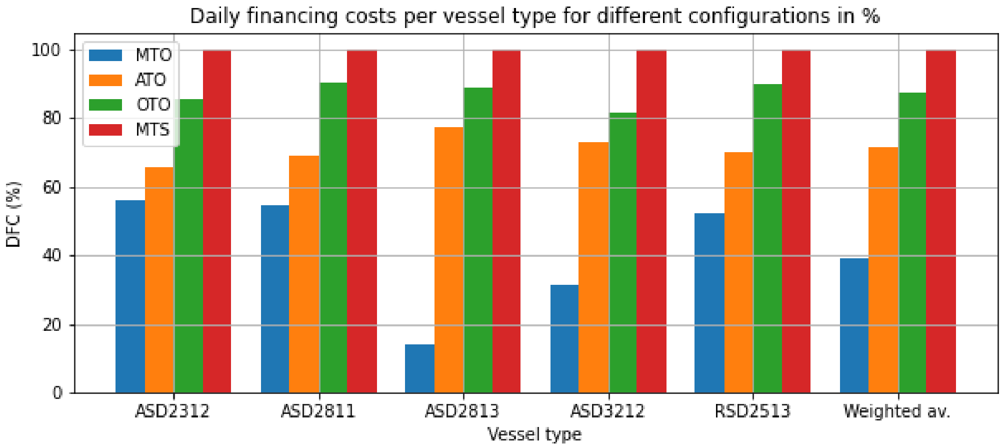

Figure 6.19: Daily financing costs for the five ship types and CODP configurations in percentage of maximum daily financing costs.

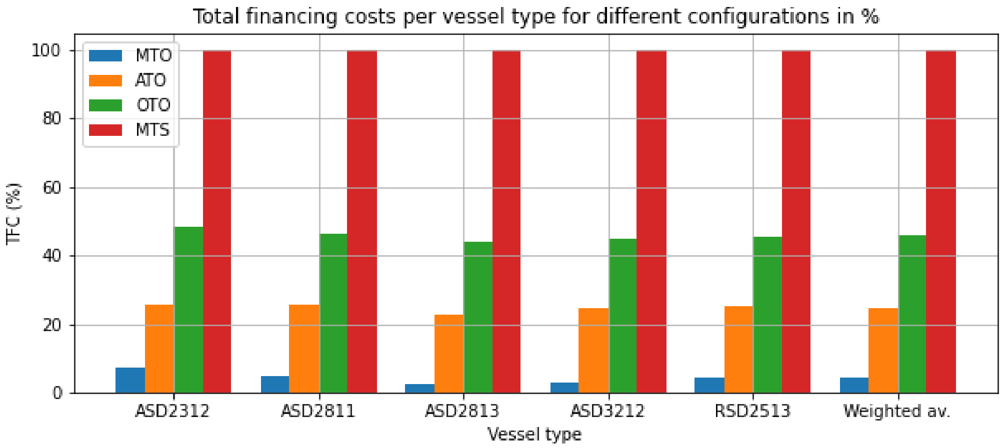

Figure 6.20: Total financing costs for the five ship types and CODP configurations in percentage of maximum total financing costs.

6.3.7. Committed parts

For each experiment, the BOMO dataset is filtered to output all parts that have to be procured at the given CODP placement. This is presented in Table 6.2.

Ship type	MTO	ATO	OTO	MTS
ASD2312	42%	77%	87%	100%
ASD2811	29%	73%	88%	100%
ASD2813	29%	73%	83%	100%
ASD3212	50%	74%	85%	100%
RSD2513	39%	76%	91%	100%

Table 6.2: Amount of parts in the committed parts data output as a percentage of total parts in the vessel.

6.3.8. Reducing supplier manufacturing lead time

Table B.6 and Figures 6.21 - 6.25 show the additional experimentation of the $SMLT_p$ for the high-value long lead time items. The effects can be seen clearly in the MTO configuration: for 3 out of 5 vessels, a reduction of 10% can reduce the risk exposure and daily financing costs by around 20 percentage points. For the ASD2312 vessel, this can be reduced by a total of 43 percentage points. This highlights the importance of supplier lead times for engines, thrusters, and generator sets and encourages the company to push its suppliers for shorter lead times.

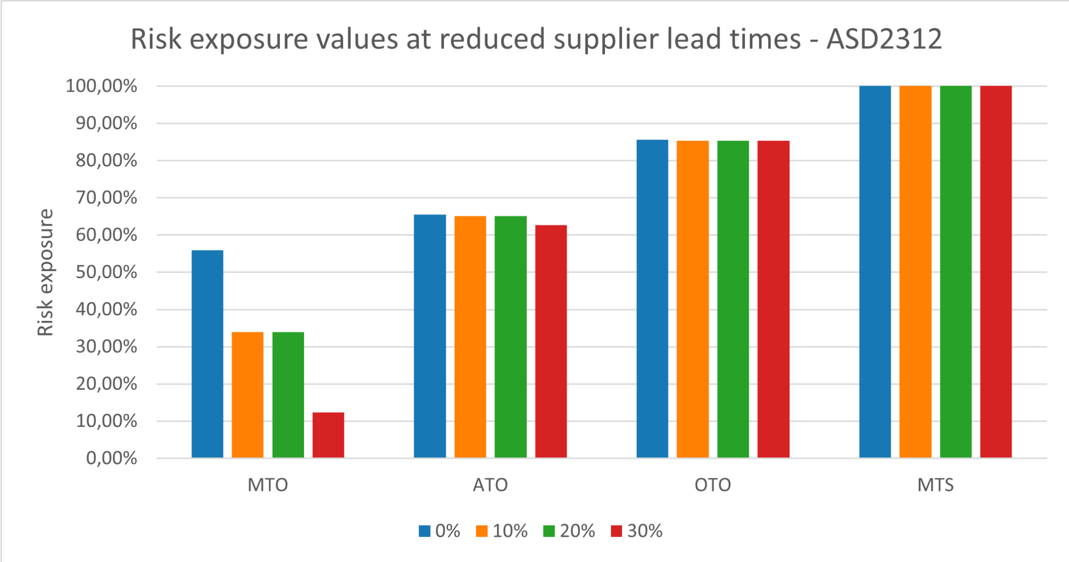

Figure 6.21: The effect of supplier lead time reduction on the risk exposure at different configurations for the ASD2312

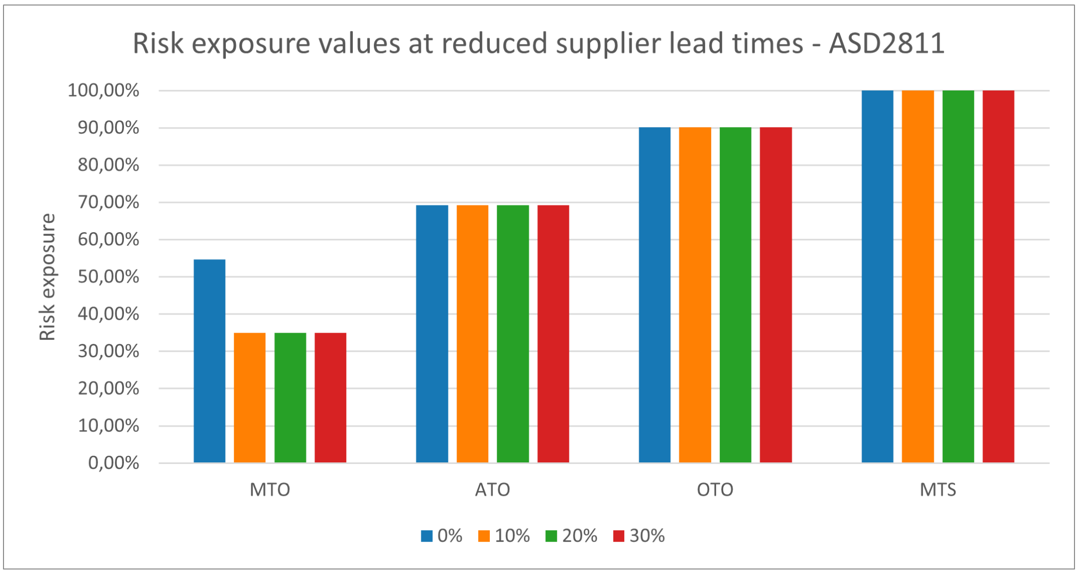

Figure 6.22: The effect of supplier lead time reduction on the risk exposure at different configurations for the ASD2811

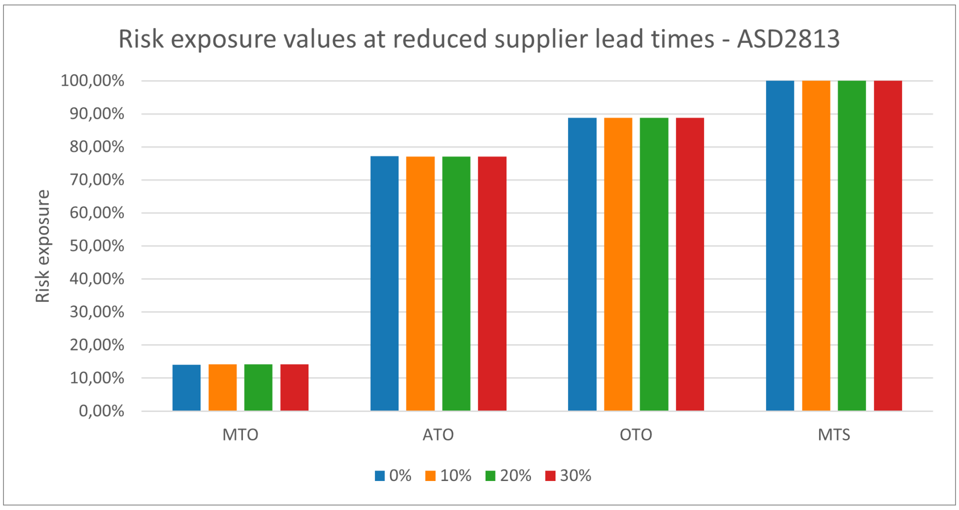

Figure 6.23: The effect of supplier lead time reduction on the risk exposure at different configurations for the ASD2813

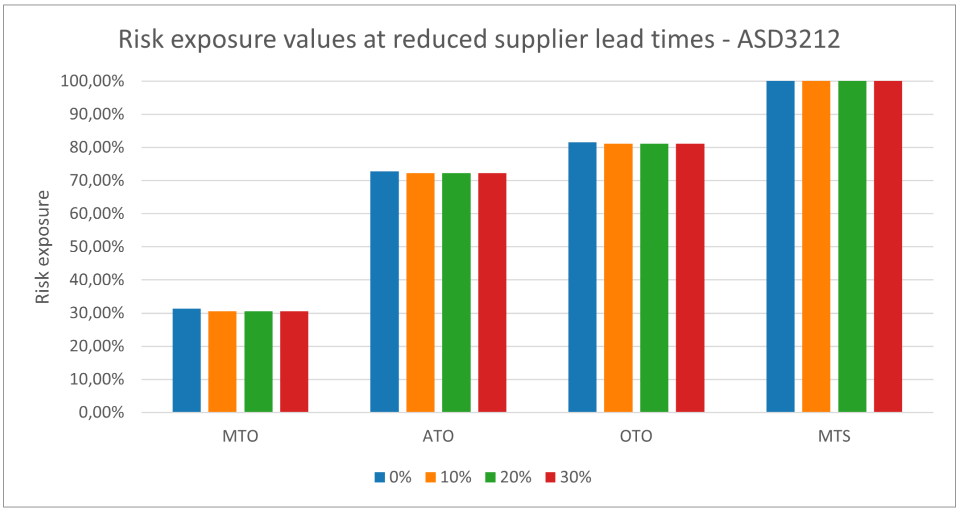

Figure 6.24: The effect of supplier lead time reduction on the risk exposure at different configurations for the ASD3212

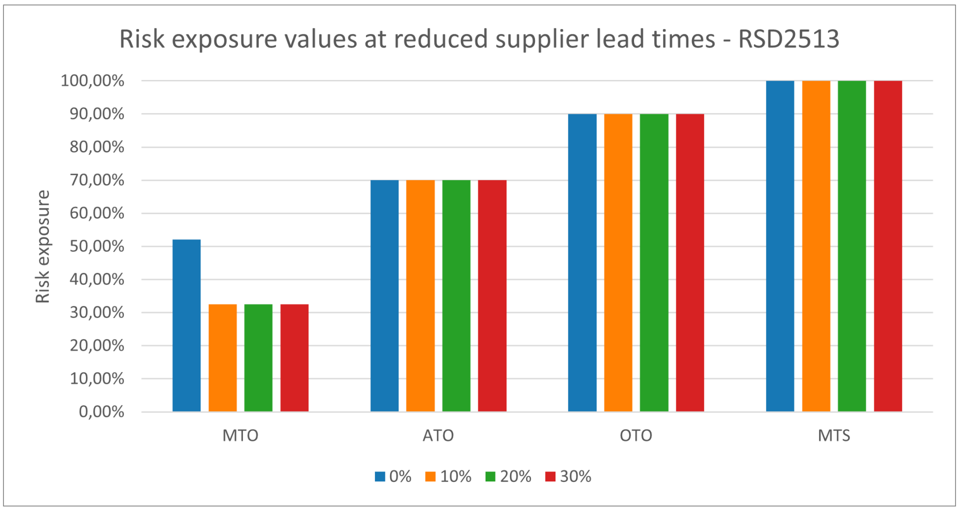

Figure 6.25: The effect of supplier lead time reduction on the risk exposure at different configurations for the RSD2513

6.4. Conclusion

By experimenting with the model presented in Chapter 4, the research question can be answered in a data-driven way:

What are the costs of delivery lead time adaption for Damen's tugboat production?

This chapter has shown how the system's KPIs are plotted over the project timeline for each vessel, including the KPIs of the four configurations for each vessel. On average:

- the MTO strategy reduces risk exposure and daily financing costs by 61% and total financing costs by 96% at an increased lead time of 407 days.
- the ATO strategy reduces risk exposure and daily financing costs by 29% and total financing costs by 76% at an increased lead time of 288 days.
- the OTO strategy reduces risk exposure and daily financing costs by 12% and total financing costs by 54% at an increased lead time of 195 days.

Purely based on financial costs, the MTO strategy is subject to the least risk exposure and financing costs, but adds more than a year of waiting time for the customer.

Additionally, twenty databases are generated that entail all parts that must be procured given each configuration.

Finally, the impact of supplier manufacturing lead time is evaluated for engines, thrusters and generator sets. Risk exposure can be significantly reduced for the MTO configuration with a 10% or 30% reduction for the ASD2312, ASD2811, and RSD2513.

7
Conclusion

1. ***What are delivery lead time costs, and how does this relate to the production configuration?***

   The delivery lead time depends on where the CODP is placed within the production planning. The ATO configuration has a longer delivery lead time than the MTS configuration but reduces the risk of inaccurate forecasting. The delivery lead time costs are related to the production process's material costs.

2. ***What is the Bill of Materials and Operations, and what is the relationship to the delivery lead time costs?***

   The BOMO is a comprehensive list of all components, parts and materials and their manufacturing lead time or activity timeline within the production process. The material value of this process can be plotted on a value-added curve. With this information, an accurate value analysis for the total runtime of the process, such as the costs of shortening or extending the delivery lead time.

3. ***What are the key aspects of Damen's tugboat production and which data is available?***

   The tugboat production system is analysed using a black box and CATWOE analysis, followed by a case-specific analysis of tugboat production at Damen. Production can be split into several phases, the most critical being hull fabrication and outfitting due to their time length, labour intensity and material value added. The ATO configuration can be implemented by shifting the CODP earlier onto the production timeline, resulting in a relationship between material value and delivery lead time. Finally, the data available at the company is presented, the most important being the BOMs, supplier data, historical order data and template planning.

4. ***How can the tugboat production be modelled, and what are the key data elements?***

   To model the tugboat production focusing on material value and financing costs, a conceptual model is presented as a three-step process consisting of importing and preparing available data, generating a BOMO database, and performing value analysis on the BOMO data. The inputs of the model are the BOM, BOO, Supplier data and transport data, which are merged to form the BOMO data set. The BOMO generation process is discussed and the mathematics behind the key data elements is shown, followed by a clarification of the value analysis profiles. Finally, the complete process of the three-step model is presented.

5. ***How can the model be validated and how does this relate to the standard method to calculate delivery lead time adaption?***

   Despite a misalignment between current knowledge and the knowledge needed to use the standard lead-time adaptation cost method, a proposition was introduced on incorporating the standard lead-time adaptation method into this thesis. The verification step consisted of two distinct tests. Scenario testing demonstrated that the model performed as intended, while parameter tuning confirmed all our hypotheses. Consequently, the model has been successfully verified. Lastly, the model is subjected to real-world data during the validation phase and compared the outcomes. The model exhibited an average error 7%.

6. ***What are the costs of delivery lead time adaption for Damen's tugboat production?***

   The case study data is used in the model and the system's KPIs are plotted over the project timeline for each vessel, including the KPIs of the four configurations for each vessel. On average:

   - the MTO strategy reduces risk exposure and daily financing costs by 61% and total financing costs by 96% at an increased lead time of 407 days.
   - the ATO strategy reduces risk exposure and daily financing costs by 29% and total financing costs by 76% at an increased lead time of 288 days.
   - the OTO strategy reduces risk exposure and daily financing costs by 12% and total financing costs by 54% at an increased lead time of 195 days.

   For each vessel and configuration a database is generated, which entail all parts that must be procured if the configuration is chosen in the future. Additionally, the importance of shorter manufacturing lead time is highlighted with experiments on high-value, long lead time items used in tugs. These items were evaluated by changing the associated supplier manufacturing lead time to see the impact on risk exposure and financing cost at the four configurations. Due to the long lead times, these items mostly impact the MTO configuration, but significant reductions can be achieved with a reduction of the supplier manufacturing lead time by 10% and 30% for the ASD2312, ASD2811, and RSD2513.

How can the costs of adapting delivery lead time be quantified with the help of the Bill of Materials and Operations when implementing a different configuration within Damen's tugboat production?

The costs of adapting the delivery lead time can be quantified with a three-step process of:

1. importing necessary part data,
2. merging the BOM, BOO, supplier and transport data into a BOMO dataset
3. using the BOMO as a tool to quantify the risk exposure and financing costs over time, to compare different production configuration configurations

This process compares four configurations for the five most standardised tugboats using a case study at Damen.

The MTO configuration is the production configuration with the lowest risk exposure and financing costs. On average, the delivery lead time is increased by 407 days, the risk exposure is decreased by 61 %, and the financing costs are reduced by 96 %. Due to unknown customer needs and preferences, the two other production configurations should also be considered.

Additionally, the impact of supplier manufacturing lead time is evaluated for engines, thrusters and generator sets. Risk exposure can be significantly reduced for the MTO configuration with a 10% or 30% reduction for the ASD2312, ASD2811, and RSD2513.

8 Limitations and recommendations

8.1. Limitations

This research presents a model of the real tug boat production system and to quote the British statistician George Box:

"All models are wrong, but some are useful"

Therefore, it is important to establish the limitations of this research and the model presented. This section discusses the limitations regarding the data, the model, and the evaluation and some other notable limitations.

8.1.1. Data limitations

This research is constrained by the availability and quality of data. The tugboat production system has extensive databases whose accuracy is not guaranteed, and data may be outdated. Additionally, the databases are subject to errors or inconsistencies, particularly given the involvement of multiple personnel in the ERP system, increasing the likelihood of human error. Other limitations regarding the data are due to suppliers, as these are not proactively updating the manufacturer on price increases.

8.1.2. Model limitations

The findings and conclusions drawn from the Damen case study may not directly apply to other contexts or industries. The specific characteristics of Damen's tugboat production system may limit the generalisability of the results to broader manufacturing settings. On the other hand, the complexity of the model and analysis methodology may introduce potential sources of error or bias. It's important to acknowledge any limitations in the model's ability to fully capture the nuances of the tugboat production process and financial dynamics.

8.1.3. Evaluation limitations

As mentioned, customer needs and preferences are unknown, making evaluating the importance of delivery lead time in relation to financial risk and costs challenging. The model and analysis also rely on assumptions about the tugboat production process. Any inaccuracies or uncertainties in these assumptions could affect the validity of the results.

8.1.4. Other limitations

The research is subject to time constraints, which could impact the depth and breadth of the analysis. Perfecting the model and kink-out irregularities in the data is time-consuming, especially considering the extensive size of the datasets used. The limited time also restricts the ability to explore alternative scenarios, conduct additional sensitivity analyses, or validate the findings through extended empirical research. Other external factors beyond the scope of the research, such as changes in market conditions, technological advancements, and changes in vessel design, influence the study's outcomes and implications.

8.2. Research Recommendations

This research has shown the limitations that can be used to identify opportunities. This section discusses possible recommendations for further research.

- The tugboat production system has many sides. This research focuses on financing and risk, but other aspects are equally important. On part level, research into which parts should be provided with a safety stock or which should be JIT delivered to the yard could be insightful.
- This research sees each vessel as an independent project. The production system shown is a standardised process, which means that the production could also be modelled as a whole, where multiple vessels can be planned to produce, and broader analyses can be made - such as modularity and part commonality.
- The location for production is now a fixed parameter but could also be a variable. The production system could be modelled with several yards worldwide, and an optimisation problem could investigate the best locations to build the next vessel depending on market demand and yard availability.

8.3. Company Recommendations

This research primarily relies on the tugboat production at Damen, so these are the company-specific recommendations.

Adapt to process-driven production. This research presents a model approach for tugboat production, which can be seen as a process of material coming in and tugboats coming out. With highly standardised products, this system should be a process instead of the current project-oriented manner.

Improve data quality. As a significant part of this thesis was spent on understanding and merging data, this should ideally be governed in one database. Especially since two environments had to be retrieved due to data segregation. At the time of writing, a new ERP system has been launched. Ideally, the data from this research should be considered for a standard BOMO overview generation for quicker analysis in the future.

Reduce man-hours involved in the procurement of parts. Increasing standard-bought items when a product is final means fewer man-hours are involved and less human error is involved. In a simple example, the knife cuts on both edges: If a part is procured too early, overall financing costs increase, as opposed to a late procurement, which halts overall production of the product, possibly increasing financing costs even more. Less man-hours equals less costs as well.

Increase standardised parts. As vessels differ in size and options, there should ideally be as less other differentiation. Standardising parts across the product platform makes the step to process-oriented working easier, and the supply chain will perform better.

Market research. This research highlights the unknown factor of customer preference. Benchmarking the value of delivery lead time is essential to make a data-based strategic decision on the placement of the CODP.

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A

Scientific paper

Reducing risk exposure and financing cost by increasing delivery lead time - a Damen Shipyards case study

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***Abstract*—The tugboat industry faces the challenge of adapting its supply chain to meet fluctuating market demands and customer customization needs while managing low order predictability. This study investigates the transition from a Make-to-Stock (MTS) to alternative production configurations—Assemble-to-Order (ATO) and Make-to-Order (MTO)—and their impact on Damen Shipyards' tugboat production. Utilizing a Bill of Materials and Operations (BOMO) approach, the study develops a mathematical algorithm to quantify financial effects, emphasizing risk exposure and financing costs. Findings suggest that the MTO configuration, despite increased delivery lead times, significantly reduces risk and financing costs.**

***Index Terms*—Production Strategy, Production Configuration, Make-to-Stock, Assemble-to-Order, Make-to-Order, Tugboat Production, Risk Exposure, Financial Cost, Bill of Materials, Bill of Operations, Bill of Materials and Operations**

I. Introduction

The global maritime industry is characterized by fluctuating market demands and evolving customer requirements. (Arnold et al., 2008) Damen Shipyards, a leader in the tugboat industry, faces challenges in aligning its production strategies with these dynamic conditions. Traditional Make-to-Stock (MTS) models are less viable due to the unpredictability of orders and the increasing demand for customized solutions. To address these challenges, this study explores alternative production configurations, particularly Assemble-to-Order (ATO) and Make-to-Order (MTO).

The primary issue for Damen Shipyards is balancing investment risk and customer satisfaction. Transitioning from MTS to ATO or MTO configurations introduces longer delivery lead times, potentially impacting customer satisfaction. However, these configurations may reduce risk exposure and financing costs. The study aims to quantify these trade-offs using a comprehensive Bill of Materials and Operations (BOMO) approach.

The challenge is implementing a production strategy accommodating customer-specific requirements and market volatility while minimizing financial risks and costs. (Saeed et al., 2019) This involves creating a model to analyse delivery lead times, material costs, and production sequences. This will be tackled by answering the following research question:

How can the costs of adapting delivery lead time be quantified with the help of the Bill of Materials and Operations when implementing a different configuration within Damen's tugboat production?

The research employs a mathematical algorithm integrating BOM and BOO data to form the BOMO dataset. (Jiao et al., 2000) This dataset is analyzed to assess risk exposure and financing costs over time. The methodology involves data collection from Damen Shipyards, model development, scenario testing, and validation.

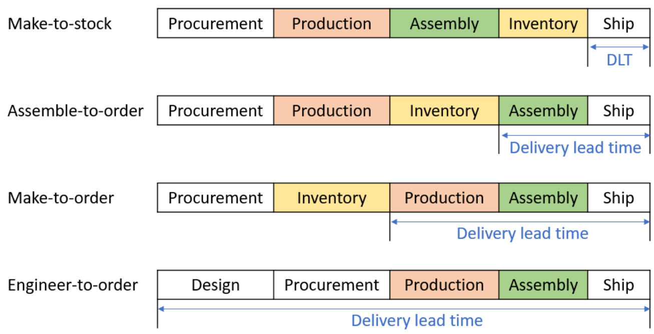

Figure 1. The four basic production configurations and their delivery lead times. (Arnold et al., 2008)

II. Literature review

A. Delivery lead time and production configuration

Lead time, the period between order placement and delivery is crucial in manufacturing. (Sen et al., 2000, Dolgui et al., 2008) It impacts inventory levels, customer satisfaction, and production efficiency. Various production configurations offer different approaches to managing delivery lead time, presented in Figure 1. The different characteristics are shown in Table I

Table I
Relative characteristics of MTS, ATO, MTO and ETO production processes. (Olhager, 2010; Wemmerlöv, 1984)

Aspect	Make-to-stock	Assemble-to-order	Make-to-order/ Engineer-to-order
Customer input	🔴	🟡🟡	🟢🟢🟢
Lead time	🟢	🟡🟡	🔴🔴🔴
Product variety	🟢🟢🟢	🟡🟡	🔴
Production volume size	🟢🟢🟢	🟡🟡	🔴
Production planning	Forecasting	Forecasting and order-driven	Order-driven
Handling demand uncertainty	Safety stock units	Overplanning of components and subassemblies	Little uncertainty exists

The Customer Order Decoupling Point (CODP) is where the product is configured to meet specific customer requirements. (Hoekstra et al., 1992, Chen et al., 2000, Naylor et al., 1999) It influences lead time and production flexibility. (Amir, 2011)

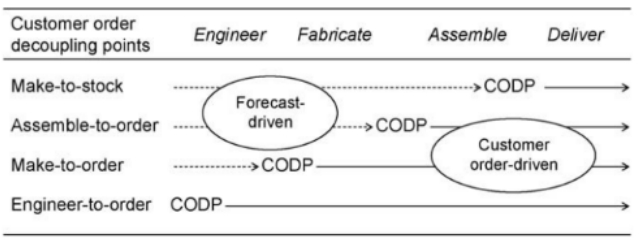

Figure 2. Different placements of the CODP. (Olhager, 2010)

ATO combines the benefits of MTS and MTO, allowing for customization with shorter lead times. (Atan et al., 2017, Nadar et al., 2014) It involves keeping an inventory of subcomponents and assembling them per customer specifications. (Deck, 1997, Xu et al., 2012, Seepersad et al., 2000) Increasing delivery lead times in ATO production reduces material investments made into the project at the time of the CODP.

B. Bill of Materials & Operations

The BOMO approach integrates the Bill of Materials (BOM) with the Bill of Operations (BOO), providing a comprehensive view of material costs and production sequences. (Jiao et al., 2000) It is a strategic tool for managing lead times and financial risks. (Arnold et al., 2008)

Effective material management is essential for reducing lead times and minimizing costs. (Pereira et al., 2020, Gross, 2019) The BOMO approach aids in optimizing material flow and production schedules.

The BOMO dataset allows for detailed analysis of delivery lead times, helping to identify bottlenecks and opportunities for improvement. Jiao et al., 2000 Thus, the BOMO approach offers a promising method for this analysis.

III. Tugboat production system

A. System analysis

The tugboat production system involves complex processes and requires a strategic approach to effectively manage lead times and costs. System analysis tools such as Black box analysis (Figure 3) help in understanding the production system and identifying key factors influencing lead times and costs. The system inputs and outputs revolve around its transformation: material goes into the system and is converted into completed tugboats.

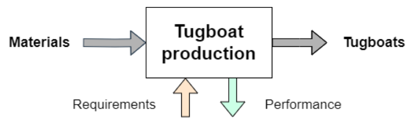

Figure 3. General overview of the black box model

1) Requirements: The requirements of the system are customer orders, design specification and capacity. Customer orders are an important requirement in this system, as these drive the demand for the manufacturers. When a customer order is placed early, there is room for customisation of the product. This means the design specifications can be altered at a customer's request.

The design specifications include engineering drawings and each vessel's corresponding Bill of Materials. This design must be completed according to the manufacturing steps specified in the Bill of Operations. When the production system includes a whole portfolio of vessels, the ships must be manufactured according to the portfolio planning.

The system is also bound to the capacity of the real-world situation, where this paper mainly focuses on capital requirements. This constraint dictates the limit on investments allocated towards materials, labour costs, and yard space, among other essential resources.

2) Performance: Performance is measured in efficiency and cost management. Production efficiency is measured by production yield, manufacturing lead time, capacity utilization, labour productivity and material waste.

Cost management is measured in production cost and equipment downtime. Production cost quantifies the average expenditure incurred in manufacturing for each vessel, and equipment downtime measures the time machinery and equipment are not operational.

The main performance in this paper is focused on cost management, which induces exposure to risk and investment costs.

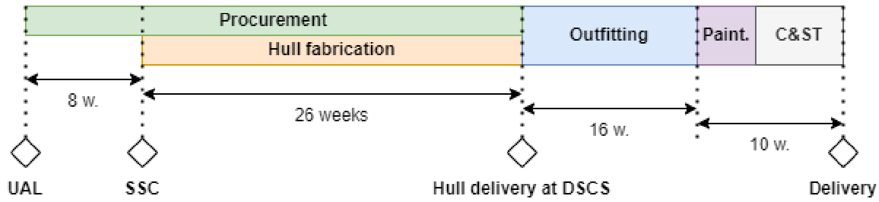

Figure 4. Example project timeline with average expected durations in weeks and milestones.

B. Tugboat production

The production of tugboats roughly spans one year in fabrication lead time and can be split into four phases. (Rose and Coenen, 2016)

1) Hull fabrication
2) Outfitting
3) Painting
4) Commissioning & sea trials

C. Production configuration

The current configuration at Damen is making ships to stock. Figure 5 presents three alternative configurations for the shipbuilding production configuration. After hull completion, the CODP can be placed as the Outfit to Order configuration. The other option is to place the CODP before the hull assembly phase begins. This means that block units are shelved until the client order is final. The last option is implementing the MTO configuration and placing the CODP before all production steps.

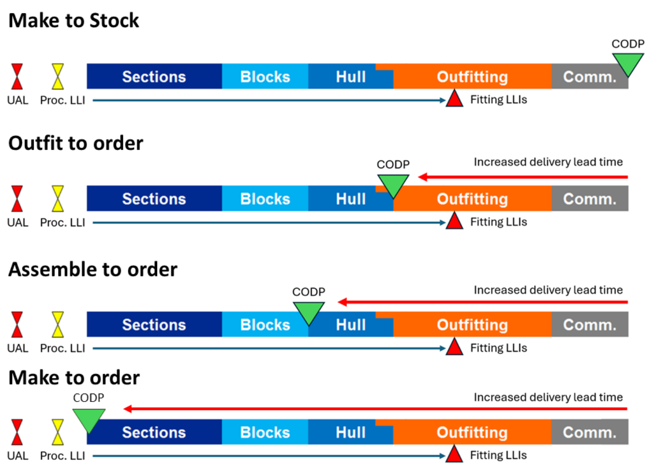

Figure 5. The current and three alternative production configurations. (Reiff, 2016)

A notable relationship shown in the figure is the procurement of material, displayed as yellow sandglass—procurement of long lead items (LLIs). Shifting the CODP means that some components have to be procured beforehand; otherwise, the project cannot continue. If all the supply and transport lead times are known, which items are LLIs and have to be procured, and the committed material value can be calculated.

If the CODP placement date is considered as T_{CODP}, the fitting date of a part as $T_{fitting}$ and the supply and transport lead times as $LT_{procurement}$ and $LT_{transport}$; then the stock items can be defined as all the parts where the following formula is true:

$$T_{CODP} < T_{fitting} - LT_{procurement} - LT_{transport}$$

IV. Mathematical Model

The mathematical model scopes on the BOM, BOO and additional data to compute a financial analysis following an increase in delivery lead time based on the presented configurations.

A. Inputs

The BOM lists all materials and amounts needed to build a tugboat, along with the activity in which each part is used in the production process. The BOO lists the activities and the planned start date of each activity. Supplier data lists the supplier-specified data for each part, such as price, currency, discount and conversion rate and manufacturing lead time. Transport data specifies the delivery location of parts and influences the expected. Lastly, the configuration specifies which production configurations to calculate.

B. Outputs

1) KPIs: The primary performance indicator for customers is delivery lead time, measured as the number of days between the CODP and the vessel's delivery date. In financial terms, risk exposure is the potential monetary loss from investments in a stock portfolio or creditor default. Daily financing costs are the nominal financial costs associated with product financing, including daily interest payments on invested capital. Total financing costs sum the daily financial costs from the project's start to the CODP, varying by configuration.

2) Value profiles: Value profiles graphically represent risk exposure, daily, and total financing costs over the project timeline. This evaluation can be linked to changes in delivery lead time.

3) Committed parts: The model must generate a list of all necessary components to determine the parts comprising the total investment amount. This list includes parts available at the yard and those that must be procured to meet delivery schedules.

C. Proposed model

A relationship exists between delivery lead time and material value used in production, which relates to risk exposure and investment cost, which can be quantified using the BOMO. Figure 6 visually represents a three-step process of how the model transforms raw data into a value analysis.

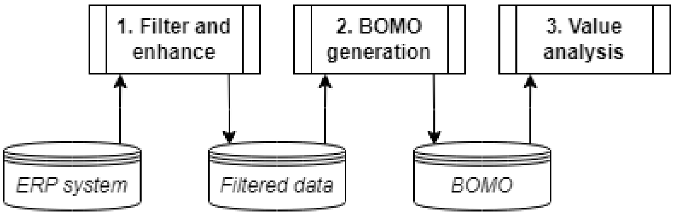

Figure 6. Three-step process.

1) BOMO generation: The BOMO is created by iteratively merging the input databases per part using a lookup function. The parameters are shown in Table II.

The loop starts by finding the part's specific supplier data. Because the input data is segregated into several price attributes, it has to be transformed into the price per part in euros. This is done with the help of a callable Currency function that combines the segregated data and returns the preferred parameter.

The second step in the loop is to find the activity tied to the part in the BOO dataset and calculate how many days the part spends on the yard, defined as the Date to Delivery.

The last step is to check where the part is supposed to be delivered. If it is not directly delivered, then the lead times for warehousing and transport to the yard must be considered. Then, the latest possible procurement date is calculated using specified lead times for each part, such as supplier manufacturing lead time, transport time, warehouse times, and buffer times.

Table II
BOMO PARAMETERS

BOMO parameter	Description
P_p	Part number
PD_p	Part description
A_p	Amount of part
SP_p	Subproject ID
Act_p	Activity ID
S_p	Supplier name
PpP_p	Price per part in Euro
AV_p	Added value in Euro
$SMLT_p$	Supplier manufacturing lead time
DTD_p	Days between the date the part is needed on the yard and the delivery date of the vessel
$DirD_p$	Binary value: 0 if the part is directly delivered, 1 if not
$PurD_p$	Days between the purchase and delivery date of the vessel

The loop process is as follows:

- Import BOM parameters for all parts
- Find delivery date of vessel in BOO data
- Initiate values for
  - Warehouse time DSGo as $WHTDSGo$
  - Transport time DSGo to DSCS as T
  - Warehouse time DSCS as $WHTDSCS$
  - Buffer time as $BufferDSCS$
  - Currency exchange rates as ExR_{curr}
- For each part P_p:
  - Find supplier data
    * If supplier is DSGo: search part P_p in DSGo SFPP database
    * Else: search part P_p in DSCS SFPP database
    * Return tho BOMO dataset:
      · Supplier name S_p
      · Manufacturing lead time $SMLT_p$
      · Price per part $PpP_p = ExR(Curr_p) * PpC_p * \frac{100-Disc_p}{100} * PCF_p$
      · Added value $AV_p = PpP_p * Ap$
  - Find BOO data
    * If Act_a is not found, or $Act_a >> AS(Delivery)$, then $AS_a = AS(Delivery)$
    * Calculate $DTD_p = AS(Delivery) - AS_a$
    * Return DTD_p
  - Find transport data
    * If the delivery address is DSGo: $DirD_p = 1$
    * Else: $DirDp = 0$
    * Calculate purchase date: $PurD_p = DTD_p + WHTDSCS + BufferDSCS + DirD_p * (WHTDSGo + T)$
    * Return $PurD_p$

2) Value analysis: Risk exposure over time is calculated by summating the material costs incurred across different time periods. The total material cost associated with each part is denoted as AV_p in the BOMO, while the moment of commitment to purchase the part is indicated by $PurD_p$. A two-dimensional index CV_{dp} is created, representing the risk exposure for part p at time period d.

$$CV_{dp} = AV_p \times x_d \tag{IV-C.1}$$

Where x_d is a binary variable defined as follows:

$$x_d = \begin{cases} 1 & \text{if d is } PurD_p \\ 0 & \text{otherwise} \end{cases} \tag{IV-C.2}$$

This equation ensures that CV_{dp} is equal to AV_p only when the time period d corresponds to the purchase date $PurD_p$, and 0 otherwise. Such a representation allows for precise tracking of the risk exposure over time and across different parts of the system. The risk exposure equals the accumulated commitment value over time.

$$EP(t) = \sum_{d=0}^{t} \sum_{p \in P} CV_{dp} \qquad with \qquad 0 < t < length(d) \tag{IV-C.3}$$

The daily financing costs can be found by multiplying the risk exposure EP with the daily interest rate DIR.

$$DFC(t) = EP(t) * DIR \tag{IV-C.4}$$

The total financing costs TFC over time t are the integration of the daily financing cost:

$$TFC(t) = \sum_{i=0}^{t} DFC(i) \tag{IV-C.5}$$

D. *Verification and validation*

The model is verified using scenario testing and parameter tuning with hand-calculated hypotheses. In both tests, all hypotheses were supported. The model is validated by comparing model output to real-world outcomes, and the model has an average error of 7%.

V. Case study results

Damen's five most sold vessels are considered in the case study and evaluated using the presented model. The first experiment compares the three alternative configurations, ATO, OTO and MTO, to the baseline MTS configuration. The second experiment analyses the effect of reducing supplier lead time of LLIs on risk exposure at the given configurations.

A. *Configuration comparison*

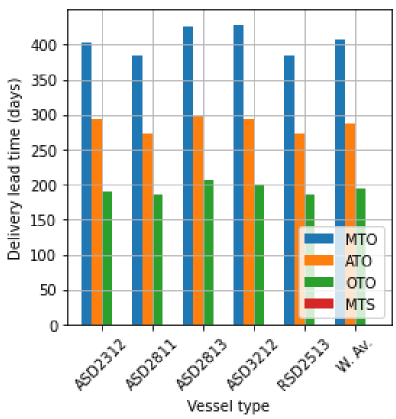

Figure 7. Delivery lead time for the five ship types and CODP configurations in percentage project time.

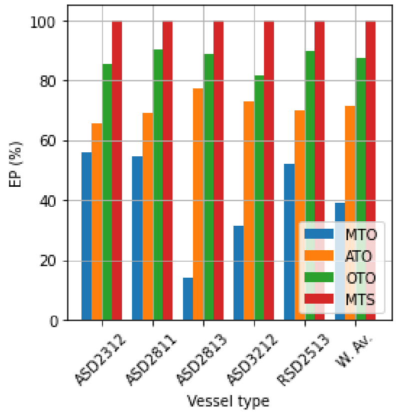

Figure 8. Risk exposure for the five ship types and CODP configurations in percentage of total risk exposure.

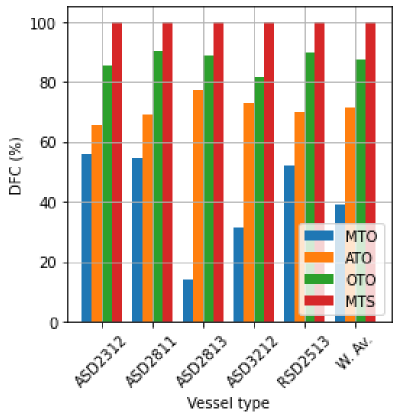

Figure 9. Daily financing costs for the five ship types and CODP configurations in percentage of maximum daily financing costs.

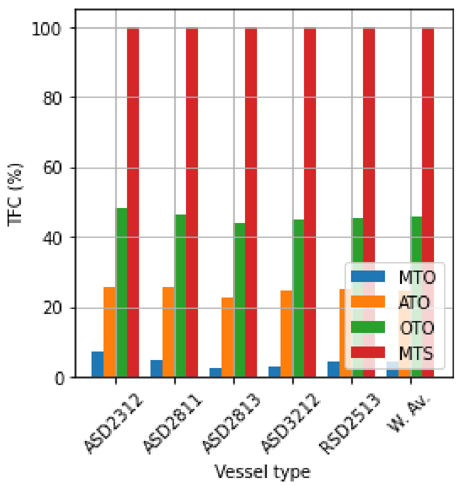

Figure 10. Total financing costs for the five ship types and CODP configurations in percentage of maximum total financing costs.

B. Reducing LLI supplier lead time

Reducing the supplier lead time of the LLI had a particular effect on the EP value of the MTO configuration. With 10% reduction, the risk exposure drops for the ASD2312, ASD 2811 and RSD2513. With 30% reduction, the decrease continues for the ASD2312. These results highlight the importance of supplier lead times on financial risk.

Table III
THE EFFECT OF REDUCING SUPPLIER MANUFACTURING LEAD TIME ON THE RISK EXPOSURE AN DAILY FINANCING COSTS.

LT reduction	0%	10%	20%	30%
ASD2312, MTO	55.9%	33.9%	33.9%	12.4%
ASD2811, MTO	54.6%	35.0%	35.0%	35.0%
ASD2813, MTO	14.1%	14.2%	14.2%	14.2%
ASD3212, MTO	31.3%	30.6%	30.6%	30.6%
RSD2513, MTO	52.1%	32.5%	32.5%	32.5%

VI. CONCLUSION

The costs of adapting the delivery lead time can be quantified with a three-step process of:

1) importing necessary part data,
2) merging the BOM, BOO, supplier and transport data into a BOMO dataset
3) using the BOMO as a tool to quantify the risk exposure and financing costs over time, to compare different production configuration configurations

This process compares four configurations for the five most standardised tugboats using a case study at Damen.

The MTO configuration is the production configuration with the lowest risk exposure and financing costs. On average, the delivery lead time is increased by 407 days, the risk exposure is decreased by 61 %, and the financing costs are reduced by 96 %. Due to unknown customer needs and preferences, the two other production configurations should also be considered.

Additionally, the importance of shorter manufacturing lead time is highlighted with experiments on high-value, long lead time items used in tugs. These items were evaluated by changing the associated supplier manufacturing lead time to see the impact on risk exposure and financing cost at the four configurations. Due to the long lead times, these items mostly impact the MTO configuration, but significant reductions can be achieved with a reduction of the supplier manufacturing lead time by 10% and 30%

VII. RECOMMENDATIONS

As this paper considers tugboat production as a process per vessel, additional research could be valuable into the overall portfolio of the production system. Additionally, further research is needed into optimising the supply of materials on part level, such as safety stocks, JIT deliveries and other lean principles. Finally, the location of production could be made a variable in case the production system has several yards across the world.

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B Additional figures and tables

	Sold vessels
ASD2312	xx
ASD2811	xx
ASD2813	xx
ASD3212	xx
RSD2513	xx
Total	xx

Table B.1: Amount of vessels sold in the last five years. (Damen, 2024)

Ship type	MTO	ATO	OTO	MTS
ASD2312	xx	xx	xx	xx
ASD2811	xx	xx	xx	xx
ASD2813	xx	xx	xx	xx
ASD3212	xx	xx	xx	xx
RSD2513	xx	xx	xx	xx

Table B.2: Amount of parts in the committed parts data output.

Configuration:	MTO		ATO		OTO		MTS	
Unit:	k€	%	k€	%	k€	%	k€	%
ASD2312	x	55,9	x	65,5	x	85,6	x	100,0
ASD2811	x	54,6	x	69,2	x	90,1	x	100,0
ASD2813	x	14,1	x	77,2	x	88,8	x	100,0
ASD3212	x	31,3	x	72,8	x	81,6	x	100,0
RSD2513	x	52,1	x	70,0	x	90,0	x	100,0

Table B.3: Risk exposure for the five ship types and CODP configurations.

Configuration:	MTO		ATO		OTO		MTS	
Unit:	€	%	€	%	€	%	€	%
ASD2312	x	55,9	x	65,5	x	85,6	x	100,0
ASD2811	x	54,6	x	69,2	x	90,1	x	100,0
ASD2813	x	14,1	x	77,2	x	88,8	x	100,0
ASD3212	x	31,3	x	72,8	x	81,6	x	100,0
RSD2513	x	52,1	x	70,0	x	90,0	x	100,0

Table B.4: Daily financing costs in percentage for the five ship types and CODP configurations.

Configuration:	MTO		ATO		OTO		MTS	
Unit:	k€	%	k€	%	k€	%	k€	%
ASD2312	x	7,1	x	25,8	x	48,3	x	100,0
ASD2811	x	4,7	x	25,5	x	46,3	x	100,0
ASD2813	x	2,5	x	22,5	x	43,9	x	100,0
ASD3212	x	3,0	x	24,5	x	44,7	x	100,0
RSD2513	x	4,4	x	25,1	x	45,5	x	100,0

Table B.5: Total financing costs in percentage for the five ship types and CODP configurations.

ASD2312	0%	10%	20%	30%
MTO	55.9%	33.9%	33.9%	12.4%
ATO	65.5%	65.1%	65.1%	62.7%
OTO	85.6%	85.4%	85.4%	85.4%
MTS	100.0%	100.0%	100.0%	100.0%
ASD2811	0%	10%	20%	30%
MTO	54.6%	35.0%	35.0%	35.0%
ATO	69.2%	69.2%	69.2%	69.2%
OTO	90.1%	90.1%	90.1%	90.1%
MTS	100.0%	100.0%	100.0%	100.0%
ASD2813	0%	10%	20%	30%
MTO	14.1%	14.2%	14.2%	14.2%
ATO	77.2%	77.1%	77.1%	77.1%
OTO	88.8%	88.8%	88.8%	88.8%
MTS	100.0%	100.0%	100.0%	100.0%
ASD3212	0%	10%	20%	30%
MTO	31.3%	30.6%	30.6%	30.6%
ATO	72.8%	72.2%	72.2%	72.2%
OTO	81.6%	81.2%	81.2%	81.2%
MTS	100.0%	100.0%	100.0%	100.0%
RSD2513	0%	10%	20%	30%
MTO	52.1%	32.5%	32.5%	32.5%
ATO	70.0%	70.0%	70.0%	70.0%
OTO	90.0%	90.0%	90.0%	90.0%
MTS	100.0%	100.0%	100.0%	100.0%

Table B.6: The effect of reducing supplier manufacturing lead time on the risk exposure an daily financing costs.

C Interviews

The interviews aim to map the current company processes and develop know-how on extracting relevant data from the company systems. To do this, several Damen employees have been interviewed based on a semi-structured interview approach. As different roles cover the questionnaire only partly, a summary of all interview answers is given per theme and question.

C.1. Interviewees

Date	Name	Job Title	Location
1-nov-2023	x	Purchaser	DSGo
3-nov-2023	x	Material Coordinator	DSGo
10-nov-2023	x	Material Coordinator	DSGo
22-nov-2023	x	Engineering Manager	DSGo
22-nov-2023	x	Technical Manager (Tugs)	DSGo
17-nov-2023	x	Category Manager	DSGo
11-jan-2024	x	Senior Teamlead Work Preparation	DSCS
2-feb-2024	x	Planning Department Manager	DSCS

C.2. Questionnaire

The interview starts with general questions about the interviewee, such as company role, responsibility and information flow. Followed by several in-depth themes such as the building strategy, Bill of Materials and procurement.

C.3. Business process

The business process and information flow is shown in the swimlane diagram in Figure C.1.

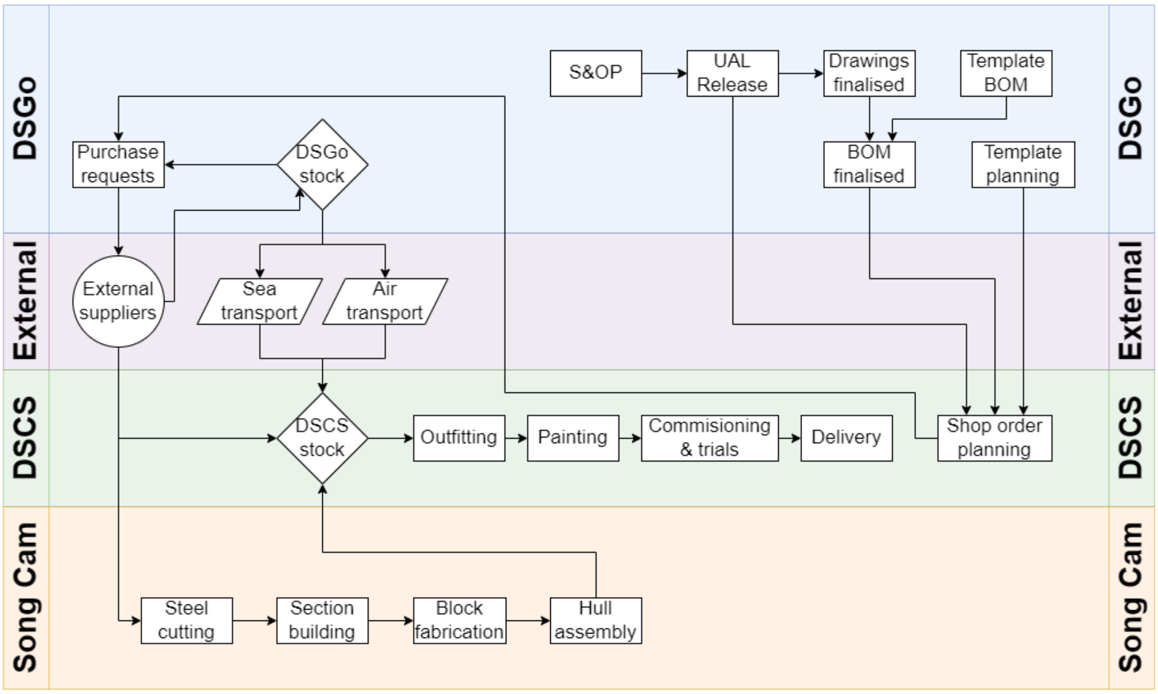

Figure C.1: Swimlane analysis of Damen's tugboat production.

C.4. Building strategy

C.4.1. What is the current building strategy at DSCS?

Damen Song Cam Shipyards (DSCS) is a joint venture between Damen Shipyards Gorinchem (DSGo) and Song Cam, a Vietnamese shipyard in Haiphong. The building strategy is split into two parts: Song Cam is responsible for delivering the hull for each project, and DSCS is responsible for the remaining construction activities. Song Cam is the "Hull Yard" and DSCS is the "Outfitting Yard"

There are two strategies for constructing tugs: push- and pull flow. Pull flow is the conventional Engineer-to-Order strategy where the project is tailored to the customer's requirements, and material is pushed through the supply chain. Push flow works in the opposite direction, where material is pulled through the chain due to forecast-driven demand. These projects are standardized vessels, and the production drives on the Make-to-Stock strategy, Damen's successful philosophy.

The product portfolio planning is updated monthly, and it decides which projects are planned for the coming two years based on market forecasts, yard availability, and the current state of the material in the supply chain.

C.4.2. What are the manufacturing steps of the building process?

Each vessel type in the portfolio has a template planning, which is a pre-defined structure with activities and milestones that is used when creating new projects. The general manufacturing steps for tugboats are:

1. Hull fabrication
   (a) Steel cutting
   (b) Section building
   (c) Hull assembly
2. Outfitting
3. Painting
4. Commissioning & sea trials (C&ST)

There are several milestones within the project timeline. For on-going projects, the milestone deviation is the important for internal communication. E.g. when the milestone for start outfitting is delayed, all subsequent activities and all related parts and materials delay too.

M1. UAL release
M2. Start steel cutting (SSC)
M3. Hull delivery at DSCS
M4. Delivery to client or stock

In the outfitting phase, a significant portion of the total material value is added to the production process and is around 12 weeks long. This is done in consecutive shop orders. A shop order is a list of work and materials for each activity. It is a loop cycle process where parts are picked from inventory and assembled onto the vessel and continues to the next shop order.

C.4.3. What is the difference in building process between different vessel types within the tugboats portfolio?

The building process is dependent on the vessel type and options and is specified in the template planning for each vessel type. As tugboats are considered highly standardised, the general manufacturing steps are similar. Exact deviations can be seen by comparing the templates in the planning software.

C.4.4. How is the data for the building process structured?

The planning software "Primavera" contains template planning structures, which is copied when a new project of that vessel type is being planned. In a nutshell: each project has a desired delivery date, the template planning is aligned with that date and the planning is determined.

Primavera can output Gantt charts, current project timelines and template project timelines. Each activity has a start and end date and is linked to the ERP system "IFS" by means of an IFS activity ID.

Parameter	Description
Activity ID	Activity identifier
Start date	Start date of the activity in dd/mm/yyyy
End date	End date of the activity in dd/mm/yyyy

C.5. Bill of Materials

C.5.1. How is the data for the building process structured?

As tugs are highly standardised, the Bill of Materials is standard as well with a template BOM. The template BOM contains all the possible items in the tug type, thus including all option. E.g. when there are two engine options, both are included in the BOM. The amount of standardised items in the BOM is around 95%, the remaining 5% are mostly options. When the project details are final, the only chosen option is transferred to the project BOM.

C.5.2. How does this relate to the building process?

The project BOM has an activity ID parameter for each part and these are already filled in the template for standard parts. When the engineering drawings and BOM is released, a planner connects the remaining parts to their respective activities, so that the shop orders and materials are correctly linked.

C.5.3. How is the Bill of Materials data structured and how reliable is this data?

The Bill of Materials is a large data set containing all engineering parameters and information. The most notable are:

Parameter	Description
Part No	Unique part number
Part description	Description of the part
MPL Required	Amount of that part needed
Provide Code	Indicate if the part is bought, made or a phantom part
Std planned item	Indicates if the part is standard or optional
Sub Project/Activity ID	Assigned Sub Project number and Activity ID
Inherited Sub Project/Activity ID	Inherited Sub Project number and Activity ID from parent part

The BOM in IFS is leading, meaning the data is highly reliable. However sometimes, when details within a project timeline are altered (e.g. options), the change is not always updated in IFS and may lead to incorrect data analysis.

C.6. Procurement

C.6.1. What is the process of material procurement?

The shop orders from DSCS are send to DSGo, with the required delivery date on the yard for the parts linked to that shop order. The ERP system calculates the latest order date for the parts based on the manufacturing lead time of the supplier, warehousing time and transport time. From this, purchase requisition lines (PRLs) are send to the purchase department with the needed date for each part in the project. The PRLs are converted by a purchaser into purchase orders lines (POLs) for each supplier. The supplier sends us an order confirmation, which is checked for the correct prices and delivery dates. All supplier data is stored in the Supplier For Purchase Part (SFPP).

C.6.2. What are the different flows of material?

There are two flow directions of material: push flow and pull flow. Push flow is material demand created at DSGo that has high priority, where material is pushed through the supply chain to ensure fast delivery to DSCS. The materials in the push flow are often incidental and not planned for. Due to the high priority, the materials are send by air transport, which is more costly than the standard sea transport.

The most common flow is pull flow and can be differentiated into local supply, normal pull flow and anonymous pull flow.

Local supply is where DSCS prefers a local supplier over DSGo, as is described in the demarcation. The demarcation is an agreement between the two entities on which material is ordered by whom.

Normal- and anonymous pull flow are procured by DSGo as described in the demarcation. In both options, material is first delivered at DSGo and send to DSCS by sea transport. On average, three containers full of material are send each week.

Normal pull flow is the normal process of procurement based on the process as described in the previous section. In normal pull flow, each part is linked to a specific project and shop order and pulled through the supply chain based on the latest need date of the DSCS yard.

Anonymous pull flow parts are ordered without a link to a specific project, usually bought in bulk and which are needed in many different ship types. These parts are bought for a standard price according to set agreements between DSCS and DSGo, called a blanket agreement.

C.6.3. What are the lead times related to procurement?

The ERP system calculates the lead times based on the following parameters:

Lead time	timespan
Manufacturing lead time	depends on supplier data
Warehouse time DSGo	7 days
Transport time DSGo to DSCS	80 days
Warehouse time DSCS	21 days
Buffer time DSCS	7 days

C.6.4. How is the procurement data structured?

The SFPP and historical transport data is structured as follows:

Parameter	**Description**
Part No	Unique part number
Part description	Description of the part
Supplier name	Name of the supplier
Supplier Manufacturing Leadtime	Lead time from order moment to delivery at site
Primary supplier	Indicates the primary supplier for this part number
Price/Curr	Unconverted price per currency as ”Currency” parameter
Currency	The currency in which the ”Price/Curr” is stated
Price Conversion Factor	Conversion factor if supplied in packages
Discount	Supplier discount rate in percentage

Parameter	**Description**
Part No	Unique part number
Delivery Address	Location at which the part is to be delivered

Table C.1: Historic order data

D

VBA code

D.1. Module 1: Data import

```
Sub ImportMain()
    StartTime = Timer
    ' ------------------ PARAMETERS ------------------ '
    ' ------------------------------------------------ '

    Dim DirLoc, BOMFile, DSGoFile, DSCSFile, a As String
    Dim FileTypes, FileNames, Cols, DestSheetNames, values As Variant
    Dim DataImp As Worksheet
    Dim i As Integer

    DirLoc = "C:\BOMO and EP\Input files\
    "

    Set DataImp = ThisWorkbook.Worksheets("DataImport")

    ' Define arrays for file types, file names, columns, and destination sheet names
    ' See "DataImport" sheet for clarification
    FileTypes = Array("BOM", "DSGo", "DSCS", "PO", "Act")
    FileNames = Array("B7", "G7", "D7", "K7", "I7")
    Cols = Array("B9", "G9", "D9", "K9", "I9")
    DestSheetNames = Array("BOM", "Supplier100", "Supplier225", "POLines", "Planning")

    Application.StatusBar = "Importing Data:"
    DoEvents

    ' ------------------ IMPORT DATA ------------------ '
    ' ------------------------------------------------- '

    ' Loop through each file type
    For i = LBound(FileTypes) To UBound(FileTypes)
        Application.StatusBar = "Importing Data: " & FileTypes(i)
        DoEvents
        ' Construct file path
        FilePath = DirLoc & DataImp.Range(FileNames(i)).Value
        ' Set destination sheet
        Set DestSheet = ThisWorkbook.Worksheets(DestSheetNames(i))
        ' Define column range
        ColRange = DataImp.Range(Cols(i), DataImp.Range(Cols(i)).End(xlDown)).Value
        ' Execute import function
        Call Import_Function(FilePath, DestSheet, ColRange)
    Next i

    Debug.Print "Import time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    ' Clear memory
    Set DataImp = Nothing
    Set DestSheet = Nothing


    ' ------------------ REFINE DATA ------------------ '
    ' ------------------------------------------------- '
```

```
    Application.StatusBar = "Refining Data: BOM"
    DoEvents

    ' -- BOM: Filter out unneeded data and split Sub Project/IFS activity -- '
    With ThisWorkbook.Worksheets("BOM")
        lastRow = .Cells(.Rows.Count, "A").End(xlUp).Row
        lastColumn = .Cells(1, Columns.Count).End(xlToLeft).Column

        ' Filter only MPL Required?
        FilterBOM = 0

        If FilterBOM = 1 Then
            'Clear any existing filters
            On Error Resume Next
              .ShowAllData
            On Error GoTo 0

            '1. Apply Filter
            .Range("A2:H2", .Range("A2:H2").End(xlDown)).AutoFilter Field:=3, Criteria1:=""

            '2. Delete Rows
            Application.DisplayAlerts = False
            .Range("A2:H2", .Range("A2:H2").End(xlDown)).SpecialCells(xlCellTypeVisible).Delete
            Application.DisplayAlerts = True

            '3. Clear Filter
            On Error Resume Next
              .ShowAllData
            On Error GoTo 0
        End If

        ' Split Sub Project/IFS activity
        ' Find columns containing IDs and inherited IDs
        SubPColumn = .Range(.Cells(1, 1), .Cells(1, lastColumn)).Find("Sub  Project/Activity", LookIn:=
             xlValues, LookAt:=xlWhole).Column
        InhSubPColumn = .Range(.Cells(1, 1), .Cells(1, lastColumn)).Find("Inherited Sub  Project/Activity
             ", LookIn:=xlValues, LookAt:=xlWhole).Column
        ' Fill array
        ReDim values(1 To lastRow, 1 To 2)
        For i = 1 To UBound(values)
            values(i, 1) = .Cells(i + 1, SubPColumn)
            values(i, 2) = .Cells(i + 1, InhSubPColumn)
        Next i

        ' Split and return values into sheet
        .Range(.Cells(1, SubPColumn), .Cells(1, InhSubPColumn)).Value = Array("Sub Project", "IFS
             Activity")
        For i = 1 To UBound(values)
            If Not IsEmpty(values(i, 1)) Then
                a = values(i, 1)
                .Cells(i + 1, SubPColumn).NumberFormat = "@"
                .Cells(i + 1, InhSubPColumn).NumberFormat = "@"
                .Cells(i + 1, SubPColumn).Value2 = Left(a, InStr(1, a, "/") - 2)
                .Cells(i + 1, InhSubPColumn).Value2 = Right(Mid(a, InStr(a, "/")), Len(Mid(a, InStr(a, "/
                   "))) - 2)
            ElseIf Not IsEmpty(values(i, 2)) Then
                a = values(i, 2)
                .Cells(i + 1, SubPColumn).NumberFormat = "@"
                .Cells(i + 1, InhSubPColumn).NumberFormat = "@"
                .Cells(i + 1, SubPColumn).Value2 = Left(a, InStr(1, a, "/") - 2)
                .Cells(i + 1, InhSubPColumn).Value2 = Right(Mid(a, InStr(a, "/")), Len(Mid(a, InStr(a, "/
                   "))) - 2)
            End If
        Next i
        .Range(.Cells(1, SubPColumn), .Cells(1, SubPColumn)).Value = Array("Sub Project", "IFS Activity")
        values = 0 ' Clear array

    End With


    Debug.Print "BOM refinement time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    ' -- PO Lines: Direct delivery -- '
    Application.StatusBar = "Refining Data: POLines"
    DoEvents

    With ThisWorkbook.Worksheets("POLines")
        lastRow = .Cells(.Rows.Count, "A").End(xlUp).Row
        values = .Range("B2:C" & lastRow).Value

        .Range("C1").Value = "Direct Delivery?"

        For j = 1 To UBound(values, 1)
```

```
            If values(j, 1) = 4 Then
                .Range("C" & j + 1).Value = "No"
            Else
                .Range("C" & j + 1).Value = "Yes"
            End If
        Next j

        values = 0 ' Clear memory
    End With

    Debug.Print "POLine refinement time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    ' -- Planning: calculate days to delivery -- '
    Application.StatusBar = "Refining Data: Planning"
    DoEvents

    With ThisWorkbook.Worksheets("Planning")
        lastRow = .Cells(.Rows.Count, "A").End(xlUp).Row

        .Range("E1").Value = "DTD"

        For i = 1 To lastRow
            If .Range("A" & i).Value = "DEL2ND" Then
                DelDate = .Range("C" & i).Value
            End If
        Next i

        For j = 2 To lastRow
            .Range("E" & j).Value = DelDate - .Range("C" & j)
        Next j

    End With

    Debug.Print "Planning refinement time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    Application.StatusBar = "Ready"

End Sub

Sub Import_Function(FilePath, DestSht, Cols)
    If FilePath = "False" Then Exit Sub

    ' ------------------ PARAMETERS ------------------ '
    ' ------------------------------------------------ '

    Dim WB As Workbook
    Dim SrcSht As Worksheet
    Dim SrcRng As Range
    Dim SrcLRow, DestLCol, ColNo As Long
    Dim SrcLCol As Long
    Dim ColName As Variant

    ' Define file and worksheet
    Set WB = Workbooks.Open(FilePath)
    Set SrcSht = WB.Worksheets(1)

    ' Define range to import
    With SrcSht
        SrcLRow = .Range("A" & Rows.Count).End(xlUp).Row          ' last row
        SrcLCol = .Cells(1, Columns.Count).End(xlToLeft).Column   ' last column
        Set SrcRng = .Range(.Cells(1, "A"), .Cells(SrcLRow, SrcLCol))
    End With

    ' ------------------ IMPORT DATA ------------------ '
    ' ------------------------------------------------ '

    ' Clear destination sheet
    DestSht.Columns.Clear

    ' Copy defined columns
    i = 1
    On Error Resume Next
    For Each ColName In Cols
        ColNo = Application.Match(ColName, SrcRng.Rows(1), 0)
        SrcRng.Columns(ColNo).Copy Destination:=DestSht.Cells(1, i)
        i = i + 1
    Next ColName
    i = 0

    ' Close import file
    WB.Close
```

```
    ' ------------------ CLEAR MEMORY ------------------ '
    ' -------------------------------------------------- '
    Set WB = Nothing
    Set SrcSht = Nothing
    Set SrcRng = Nothing
    Set SrcLRow = Nothing
    Set DestLCol = Nothing
    ColNo = 0
    SrcLCol = 0
    Set ColName = Nothing

End Sub
```

D.2. Module 2: BOMO generation

```
    Sub BOMOGeneration()
    ' ----- Initialise VBA structure ----- '
    StartTime = Timer
    Dim BOMOAry, DSGoAry, DSCSAry, PlanningAry, POLineAry, ChartAry As Variant
    Dim BomSht, BomoSht As Worksheet
    Dim appStatus As Variant
    Dim rng As Range

    With Application
        .ScreenUpdating = False
        If .StatusBar = False Then appStatus = False Else appStatus = .StatusBar
    End With

    Set BomSht = ThisWorkbook.Worksheets("BOM")
    Set BomoSht = ThisWorkbook.Worksheets("Master")
    Set DsgoSht = ThisWorkbook.Worksheets("Supplier100")
    Set DscsSht = ThisWorkbook.Worksheets("Supplier225")
    Set PlanningSht = ThisWorkbook.Worksheets("Planning")
    Set POLineSht = ThisWorkbook.Worksheets("POLines")
    Set ChartSht = ThisWorkbook.Worksheets("ExposureProfile")
    Set DashboardSht = ThisWorkbook.Worksheets("Dashboard")

    lastRow = BomSht.Cells(BomSht.Rows.Count, "A").End(xlUp).Row + 5
    ReDim BOMOAry(1 To lastRow - 1, 1 To 21)
    ' Clear excel
    BomoSht.Rows(5 & ":" & BomoSht.Rows.Count).Clear
    ChartSht.Rows(4 & ":" & ChartSht.Rows.Count).ClearContents

    ' Remove filters
    Set rng = BomoSht.Range("A4:T20000")

    rng.AutoFilter


    ' ----- BOM Data in BOMO set ----- '
    Application.StatusBar = "Processing BOM Data"
    DoEvents

    With BomSht
        lastColumn = .Cells(1, Columns.Count).End(xlToLeft).Column
        SubPColumn = .Range(.Cells(1, 1), .Cells(1, lastColumn)).Find("Sub Project", LookIn:=xlValues,
            LookAt:=xlWhole).Column
        ActColumn = .Range(.Cells(1, 1), .Cells(1, lastColumn)).Find("IFS Activity", LookIn:=xlValues,
            LookAt:=xlWhole).Column
        For i = 2 To lastRow - 5
            For j = 1 To lastColumn
                BOMOAry(i + 4, j) = .Cells(i, j).Value
                If j = SubPColumn Or j = ActColumn Then
                    .Cells(i, j).NumberFormat = "@"
                End If
            Next j
        Next i
        BomoContinue = lastColumn
    End With

    ' ----- Supplier Data in Arrays ----- '

    Application.StatusBar = "Processing DSCS Data"
    DoEvents
    Debug.Print "BOM import time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    With DscsSht
        lastRow = .Cells(.Rows.Count, "A").End(xlUp).Row
        lastColumn = .Cells(1, Columns.Count).End(xlToLeft).Column
```

```
        ReDim DSCSAry(1 To lastRow - 1, 1 To lastColumn)
        For i = 2 To lastRow
            For j = 1 To lastColumn
                DSCSAry(i - 1, j) = .Cells(i, j).Value
            Next j
        Next i
    End With

    Application.StatusBar = "Processing DSGo Data"
    DoEvents
    Debug.Print "DSCS import time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    With DsgoSht
        lastRow = .Cells(.Rows.Count, "A").End(xlUp).Row
        lastColumn = .Cells(1, Columns.Count).End(xlToLeft).Column
        ReDim DSGoAry(1 To lastRow - 1, 1 To lastColumn)
        For i = 2 To lastRow
            For j = 1 To lastColumn
                DSGoAry(i - 1, j) = .Cells(i, j).Value
            Next j
        Next i
    End With

    ' ----- Planning Data in Array ----- '
    Application.StatusBar = "Processing Planning Data"
    DoEvents

    With PlanningSht
        lastRow = .Cells(.Rows.Count, "A").End(xlUp).Row
        lastColumn = .Cells(1, Columns.Count).End(xlToLeft).Column
        ReDim PlanningAry(1 To lastRow - 1, 1 To lastColumn)
        For i = 2 To lastRow
            For j = 1 To lastColumn
                PlanningAry(i - 1, j) = .Cells(i, j).Value
            Next j
        Next i
    End With

    ' ----- PO Line Data in BOMO set ----- '
    Application.StatusBar = "Processing Planning Data"
    DoEvents

    With POLineSht
        lastRow = .Cells(.Rows.Count, "A").End(xlUp).Row
        lastColumn = .Cells(1, Columns.Count).End(xlToLeft).Column
        ReDim POLineAry(1 To lastRow - 1, 1 To lastColumn)
        For i = 2 To lastRow
            For j = 1 To lastColumn
                POLineAry(i - 1, j) = .Cells(i, j).Value
            Next j
        Next i
    End With

    ' ----- Supplier Data in BOMO set ----- '
    Application.StatusBar = "Processing BOMO"
    DoEvents
    Debug.Print "DSGo import time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    lastRow = BomSht.Cells(BomSht.Rows.Count, "A").End(xlUp).Row
    SuppColumn = BomoContinue + 1
    PriceColumn = BomoContinue + 2
    AddValueColumn = BomoContinue + 3
    MLTColumn = BomoContinue + 4
    DTDColumn = BomoContinue + 5
    DeliveryColumn = BomoContinue + 6

    DelDate = WhereInArray(PlanningAry, 1, "DEL2ND")
    MinStartDate = 0    ' initiate minimum start date for graph

    ' Input lead times from dashboard
    WHTDSGo = ThisWorkbook.Worksheets("Dashboard").Range("G3").Value
    TransportTime = ThisWorkbook.Worksheets("Dashboard").Range("G4").Value
    WHTDSCS = ThisWorkbook.Worksheets("Dashboard").Range("G5").Value
    DSCSBufferTime = ThisWorkbook.Worksheets("Dashboard").Range("G6").Value

    For i = 1 To lastRow + 4
        ' Process Supplier Data
        PartNo = BOMOAry(i, 1)
        idDSCS = WhereInArray(DSCSAry, 1, PartNo)
        If Not idDSCS = "Null" Then
            ' If DSGo is the supplier, take the DSGo supplier dataset, Else take DSCS supplier dataset
```

```
            If DSCSAry(idDSCS, 6) = "Damen Shipyards Gorinchem B.V." Or DSCSAry(idDSCS, 6) = "Dummy
                 supplier: RFC 143 (Buyer Supply)" And DSCSAry(idDSCS, 2) <= 1 Then
                idDSGo = WhereInArray(DSGoAry, 1, PartNo)
                If Not idDSGo = "Null" Then
                    BOMOAry(i, SuppColumn) = DSGoAry(idDSGo, 6)
                    BOMOAry(i, MLTColumn) = DSGoAry(idDSGo, 7)
                    BOMOAry(i, PriceColumn) = CurrencyValue(DSGoAry(idDSGo, 4), DSGoAry(idDSGo, 2), 1,
                         DSGoAry(idDSGo, 3), DSGoAry(idDSGo, 5))
                    BOMOAry(i, AddValueColumn) = CurrencyValue(DSGoAry(idDSGo, 4), DSGoAry(idDSGo, 2),
                         BOMOAry(i, 3), DSGoAry(idDSGo, 3), DSGoAry(idDSGo, 5))
                End If
            Else
                BOMOAry(i, SuppColumn) = DSCSAry(idDSCS, 6)
                BOMOAry(i, MLTColumn) = DSCSAry(idDSCS, 7)
                BOMOAry(i, PriceColumn) = CurrencyValue(DSCSAry(idDSCS, 4), DSCSAry(idDSCS, 2), 1,
                     DSCSAry(idDSCS, 3), DSCSAry(idDSCS, 5))
                BOMOAry(i, AddValueColumn) = CurrencyValue(DSCSAry(idDSCS, 4), DSCSAry(idDSCS, 2),
                     BOMOAry(i, 3), DSCSAry(idDSCS, 3), DSCSAry(idDSCS, 5))
            End If
        End If

        ' Process Planning data
        ActivityID = BOMOAry(i, 6)

        If ActivityID = Empty Then
            ActivityID = "DEL2ND"
        End If

        idPlanning = WhereInArray(PlanningAry, 1, ActivityID)
        If Not idPlanning = "Null" Then
            BOMOAry(i, DTDColumn) = PlanningAry(DelDate, 3) - PlanningAry(idPlanning, 3)
            If BOMOAry(i, DTDColumn) > 29000 Then
                BOMOAry(i, DTDColumn) = 0
            End If
        Else
            BOMOAry(i, DTDColumn) = 0
        End If

        ' Process PO Line data
        idPOLine = WhereInArray(POLineAry, 1, PartNo)
        ' Define columns
        WHTDSGoColumn = DeliveryColumn + 1
        TpTimeColumn = DeliveryColumn + 2
        WHTDSCSColumn = DeliveryColumn + 3
        DSCSBuTimeColumn = DeliveryColumn + 4
        PurchDateColumn = DeliveryColumn + 5

        If Not idPOLine = "Null" Then
            BOMOAry(i, DeliveryColumn) = POLineAry(idPOLine, 3)
        Else
            BOMOAry(i, DeliveryColumn) = "No"
        End If
        If BOMOAry(i, DeliveryColumn) = "Yes" Then
            BOMOAry(i, WHTDSGoColumn) = 0
            BOMOAry(i, TpTimeColumn) = 0
        Else
            BOMOAry(i, WHTDSGoColumn) = WHTDSGo
            BOMOAry(i, TpTimeColumn) = TransportTime
        End If
        BOMOAry(i, WHTDSCSColumn) = WHTDSCS
        BOMOAry(i, DSCSBuTimeColumn) = DSCSBufferTime
        BOMOAry(i, PurchDateColumn) = BOMOAry(i, DTDColumn) + BOMOAry(i, MLTColumn) + BOMOAry(i,
             WHTDSGoColumn) + BOMOAry(i, TpTimeColumn) + BOMOAry(i, WHTDSCSColumn) + BOMOAry(i,
             DSCSBuTimeColumn)
        If BOMOAry(i, PurchDateColumn) > MinStartDate Then
            MinStartDate = BOMOAry(i, PurchDateColumn)
        End If
        'Application.StatusBar = "Processing BOMO %" & (i / lastRow) * 100
        DoEvents
    Next i

    Application.StatusBar = "Writing BOMO"
    DoEvents
    Debug.Print "BOMO process time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")


    ' ----- Write Bomo data into Excel ----- '
    UADate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "UA"), 3)
    SSCDate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "CUT"), 3)
    SECDate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "SEC"), 3)
```

```
    ASSDate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "ASS"), 3)
    HULLDate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "HULL"), 3)
    PAINTdate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "PAINT"), 3)
    COMDate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "COM"), 3)
    RESDate = PlanningAry(WhereInArray(PlanningAry, 1, "DEL2ND"), 3) - PlanningAry(WhereInArray(
         PlanningAry, 1, "RES"), 3)

    'Write data for hull payments
    ' Write Dashboard values
    BomoSht.Range("A5:C9").Value = DashboardSht.Range("L4:N8").Value

    With BomoSht

        ' Write SSC and Hull delivery dates
        .Range("N3").Value = SSCDate
        .Range("P3").Value = HULLDate

        ' Set Std part values to 0
        .Range("G5:G9").Value = 0

        ' Calculate added values
        For i = 5 To 9
            .Range("L" & i).Value = .Range("K3").Value * .Range("C" & i).Value
        Next i
        .Range("N5:N9").Value = HULLDate

        .Range("T5").Value = SSCDate + (12 * 7)
        .Range("T6").Value = SSCDate - (16 * 7)
        .Range("T7").Value = SSCDate - (22 * 7)
        .Range("T8:T9").Value = HULLDate
    End With

    For i = 1 To 5
        For j = 1 To 21
            BOMOAry(i, j) = BomoSht.Cells(i + 4, j).Value
        Next j
    Next i


    BomoSht.Range("E5:F" & lastRow + 4).NumberFormat = "@"
    BomoSht.Range("K5:L" & lastRow + 4).Style = "Currency"
    BomoSht.Range("A5:U" & lastRow + 9).Resize(lastRow + 4, 21) = BOMOAry

    TotalMaterialValue = Application.WorksheetFunction.Sum(BomoSht.Range("L5:L" & lastRow + 9))
    BomoSht.Range("B2").Style = "Currency"
    BomoSht.Range("B2").Value = TotalMaterialValue
    rng.AutoFilter


    DoEvents
    Debug.Print "Total run time:"
    Debug.Print Format((Timer - StartTime) / 86400, "hh:mm:ss")

    With Application
        .ScreenUpdating = True
        .StatusBar = Ready
    End With

End Sub

Private Function WhereInArray(arr1 As Variant, colmn As Integer, vFind As Variant) As Variant
Dim i As Long
For i = LBound(arr1) To UBound(arr1)
    If arr1(i, colmn) = vFind Then
        WhereInArray = i
        Exit Function
    End If
Next i
'if vFind was not in the array, function returns "Nothing"
WhereInArray = Null
End Function

Function CurrencyValue(curr As Variant, price As Variant, amount As Variant, discount As Variant,
     convRate As Variant) As Variant
    cEUR = ThisWorkbook.Worksheets("Dashboard").Range("J3").Value
    cUSD = ThisWorkbook.Worksheets("Dashboard").Range("J4").Value
    cCNY = ThisWorkbook.Worksheets("Dashboard").Range("J5").Value
    cNOK = ThisWorkbook.Worksheets("Dashboard").Range("J6").Value
    cVND = ThisWorkbook.Worksheets("Dashboard").Range("J7").Value
    cSGD = ThisWorkbook.Worksheets("Dashboard").Range("J8").Value
```

```
    Select Case curr
        Case ”EUR”: CurrencyValue = cEUR * price * amount * (100 - discount) / 100 / convRate
        Case ”USD”: CurrencyValue = cUSD * price * amount * (100 - discount) / 100 / convRate
        Case ”CNY”: CurrencyValue = cCNY * price * amount * (100 - discount) / 100 / convRate
        Case ”NOK”: CurrencyValue = cNOK * price * amount * (100 - discount) / 100 / convRate
        Case ”VND”: CurrencyValue = cVND * price * amount * (100 - discount) / 100 / convRate
        Case ”SGD”: CurrencyValue = cSGD * price * amount * (100 - discount) / 100 / convRate
    End Select
End Function
```

E

Python code

E.1. Module 3: Value profile generation

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import axes3d
from matplotlib import cm
import matplotlib.colors as colors


# Define the paths to Excel files
file_paths = {
    # 'Verification': 'BOMO Verification.xlsm',
    # 'Parameter Tuning 1': 'Verification Tuning 1.xlsx',
    # 'Parameter Tuning 2': 'Verification Tuning 2.xlsx',
    # 'Parameter Tuning 3': 'Verification Tuning 3.xlsx',
    # 'Parameter Tuning 4': 'Verification Tuning 4.xlsx',
    # 'Parameter Tuning 5': 'Verification Tuning 5.xlsx',
    'ASD2312': 'BOMO ASD2312 YN513622.xlsm',
    'ASD2811': 'BOMO ASD2811 YN513226.xlsm',
    'ASD2813': 'BOMO ASD2813 YN513335.xlsm',
    'ASD3212': 'BOMO ASD3212 YN512575.xlsm',
    'RSD2513': 'BOMO RSD2513 YN515029.xlsm',
    # 'ASD2312LTR': 'BOMO ASD2312 LTR.xlsm',
    # 'ASD2811LTR': 'BOMO ASD2811 LTR.xlsm',
    # 'ASD2813LTR': 'BOMO ASD2813 LTR.xlsm',
    # 'ASD3212LTR': 'BOMO ASD3212 LTR.xlsm',
    # 'RSD2513LTR': 'BOMO RSD2513 LTR.xlsm'
}

BOO_data = {}
BOMO_data = {}
L         = {}
CV        = {}
AV        = {}
sCV       = {}
cCV       = {}
iCV       = {}
```

```
pCV           = {}
DLT           = {}
pDLT           = {}
Z           = {}
Z_new           = {}
Min           = {}
X = {}
Y = {}
pCV = {}
psCV = {}
pcCV = {}
piCV = {}
UA = {}
Cutting = {}
Assembly = {}
Hull = {}
Delivery = {}

for shiptype, path in file_paths.items():
    # Read the "Master" worksheet, skipping the first 2 rows and convert
        to data array
    # BOMO_data[shiptype] = pd.read_excel(path, sheet_name='Master')
    BOMO_data[shiptype] = pd.read_excel(path, sheet_name='Master',
        skiprows=2, header=1)
    BOMO_data[shiptype] = BOMO_data[shiptype].fillna(0)
    BOMO_array = BOMO_data[shiptype].to_numpy()
    for i in range(0, len(BOMO_array)):
        if BOMO_array[i,5] == '5.2.2.211A':
            BOMO_array[i,19] = BOMO_array[i,19] - 0.5 * BOMO_array[i,12]
            # print(BOMO_array[i,1])
            # print(BOMO_array[i,12])


    # Read "Planning" worksheet for BOO data
    BOO_data[shiptype] = pd.read_excel(path, sheet_name='Planning',
        header=0, index_col= 0)

    L[shiptype] = max(BOMO_array[:,19])

    Pid = BOMO_array[:,0]
    V   = BOMO_array[:,10]
    A   = BOMO_array[:,2]
    D   = L[shiptype] - BOMO_array[:,13]
    O   = L[shiptype] - BOMO_array[:,19]
    AV  = BOMO_array[:,11]

    I = 0.05 / 365
    R = np.arange(0, 1.05, 0.05)
    Q = np.ones_like(R) - R

    P = len(Pid)

    x = np.zeros((L[shiptype], P))


    for p in range(0,P):
```

```
        for d in range(0,L[shiptype]):
            if d == O[p]:
                x[d,p] = 1
            else:
                x[d,p] = 0


    CV[shiptype] = AV * x
    #calculate absolute values for EP, DFC and TFC
    sCV[shiptype] = CV[shiptype].sum(axis = 1)
    sCV[shiptype] = sCV[shiptype]
    cCV[shiptype] = sCV[shiptype].cumsum(axis = 0)
    iCV[shiptype] = cCV[shiptype].cumsum(axis = 0) * I

    #calculate relative values for EP, DFC and TFC
    psCV[shiptype] = sCV[shiptype] / max(sCV[shiptype])
    pcCV[shiptype] = cCV[shiptype] / max(cCV[shiptype])
    piCV[shiptype] = iCV[shiptype] / max(iCV[shiptype])

    #create DLT array
    DLT[shiptype] = np.arange(0, L[shiptype], 1)
    pDLT[shiptype] = (L[shiptype]-DLT[shiptype]) / L[shiptype]


    # Save project milestones
    UA[shiptype]        = L[shiptype] - BOO_data[shiptype].iloc[:, 3]['UA
        ']
    Cutting[shiptype]   = L[shiptype] - BOO_data[shiptype].iloc[:, 3]['
        CUT'] - 14
    Assembly[shiptype]  = L[shiptype] - BOO_data[shiptype].iloc[:, 3]['
        ASS']
    Hull[shiptype]      = L[shiptype] - BOO_data[shiptype].iloc[:, 3]['
        HULL']
    Delivery[shiptype]  = L[shiptype] - BOO_data[shiptype].iloc[:, 3]['
        DEL2ND']

#print relative EP values for lead time reduction experiments
for shiptype, path in file_paths.items():
    print(shiptype)
    print(str(round(cCV[shiptype][int(Cutting[shiptype]-1)]*100/cCV[
        shiptype][int(Delivery[shiptype]-1)],1)) + '%')
    print(str(round(cCV[shiptype][int(Assembly[shiptype]-1)]*100/cCV[
        shiptype][int(Delivery[shiptype]-1)],1)) + '%')
    print(str(round(cCV[shiptype][int(Hull[shiptype]-1)]*100/cCV[shiptype
        ][int(Delivery[shiptype]-1)],1)) + '%')
    print(str(round(cCV[shiptype][int(Delivery[shiptype]-1)]*100/cCV[
        shiptype][int(Delivery[shiptype]-1)],1)) + '%')



for shiptype, path in file_paths.items():
    plt.figure(figsize = (10,4))
    plt.plot(cCV[shiptype], label='$EP(t)$', linestyle='-')
    plt.title('Risk exposure over time for ' + shiptype)
    plt.xlabel('Project timeline (days)')
    plt.ylabel('Risk exposure value €()')
```

```
    plt.grid(True)
    plt.axvline(x = Cutting[shiptype], color = 'tab:brown', label = '$EP$
        (MTO) = € ' + str(round(cCV[shiptype][int(Cutting[shiptype]-1)
        ]/1000,1)) + 'k')
    plt.axvline(x = Assembly[shiptype], color = 'tab:orange', label = '
        $EP$(ATO) = € ' + str(round(cCV[shiptype][int(Assembly[shiptype]-1)
        ]/1000,1)) + 'k')
    plt.axvline(x = Hull[shiptype], color = 'tab:green', label = '$EP$(
        OTO) = € ' + str(round(cCV[shiptype][int(Hull[shiptype]-1)]/1000,1)
        ) + 'k')
    plt.axvline(x = Delivery[shiptype], color = 'tab:red', label = '$EP$(
        MTS) = € ' + str(round(cCV[shiptype][int(Delivery[shiptype]-1)
        ]/1000,1)) + 'k')
    plt.legend(loc = 'upper left')
    plt.savefig('plots/exposure-commitment-'+ shiptype + '.png')
    plt.show()

for shiptype, path in file_paths.items():
    plt.figure(figsize = (10,4))
    plt.plot(cCV[shiptype]*0.05/365, label='$DFC(t)$', linestyle='-')
    plt.title('Daily financing cost over time for ' + shiptype)
    plt.xlabel('Project timeline (days)')
    plt.ylabel('Daily financing costs €()')
    plt.grid(True)
    plt.axvline(x = Cutting[shiptype], color = 'tab:brown', label = '
        $DFC$(MTO = € ' + str(round(cCV[shiptype][int(Cutting[shiptype]-1)
        ]*0.05/365,2)))
    plt.axvline(x = Assembly[shiptype], color = 'tab:orange', label = '
        $DFC$(ATO) = € ' + str(round(cCV[shiptype][int(Assembly[shiptype
        ]-1)]*0.05/365,2)))
    plt.axvline(x = Hull[shiptype], color = 'tab:green', label = '$DFC$(
        OTO) = € ' + str(round(cCV[shiptype][int(Hull[shiptype]-1)
        ]*0.05/365,2)))
    plt.axvline(x = Delivery[shiptype], color = 'tab:red', label = '$DFC$
        (MTS) = € ' + str(round(cCV[shiptype][int(Delivery[shiptype]-1)
        ]*0.05/365,2)))
    plt.legend(loc = 'upper left')
    plt.savefig('plots/daily-interest-'+ shiptype + '.png')
    plt.show()

for shiptype, path in file_paths.items():
    plt.figure(figsize = (10,4))
    plt.plot(iCV[shiptype], label='$TFC(t)$', linestyle='-')
    plt.title('Total financing costs over time for ' + shiptype)
    plt.xlabel('Project timeline (days)')
    plt.ylabel('Total financing costs €()')
    plt.grid(True)
    plt.axvline(x = Cutting[shiptype], color = 'tab:brown', label = '
        $TFC$(MTO) = € ' + str(round(iCV[shiptype][int(Cutting[shiptype]-1)
        ]/1000,1)) + 'k')
    plt.axvline(x = Assembly[shiptype], color = 'tab:orange', label = '
        $TFC$(ATO) = € ' + str(round(iCV[shiptype][int(Assembly[shiptype
        ]-1)]/1000,1)) + 'k')
    plt.axvline(x = Hull[shiptype], color = 'tab:green', label = '$TFC$(
        OTO) = € ' + str(round(iCV[shiptype][int(Hull[shiptype]-1)]/1000,1)
        ) + 'k')
```

```
    plt.axvline(x = Delivery[shiptype], color = 'tab:red', label = '$TFC$
        (MTS) = €' + str(round(iCV[shiptype][int(Delivery[shiptype]-1)
        ]/1000,1)) + 'k')
    plt.legend()
    plt.savefig('plots/investment-'+ shiptype + '.png')
    plt.show()
```

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