Jarno Koivula

MODELLING AND SIMULATION OF SHIP-TO-SHORE OPERATIONS FOR PRODUCTIVITY ANALYSIS

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ABSTRACT

Jarno Koivula: Modelling and simulation of ship-to-shore operations for productivity analysis
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Significant rise of container traffic during past decades has led to adoption of larger container vessels. The increased container traffic requires more efficient operation from container terminal's logistics. In this master's thesis, a simulation model of ship-to-shore operations (STS operations) is implemented with MATLAB Simulink. STS operations cover the loading and discharging of containers onto/from container vessels with ship-to-shore cranes (STS cranes). The model generates productivity analyses of STS operations with different machinery layouts and allows to deduce the optimal number and type of STS cranes. The model calculates the individual productivities of STS cranes and measures the total time spent for operations in addition with each crane's unproductive time. A sensitivity analysis is performed to study how STS cranes' quantity and kinematic parameters influence on operations' productivity.

The implemented simulation model describes the kinematics of STS cranes and includes models of cranes' control system and a container vessel. The modelled STS cranes move realistically, and their kinematic parameters vary according to container weights and wind conditions. Cranes are equipped with single-lift spreaders and non-crossing constraints between adjacent cranes are considered. The implemented control system model controls the operations in a way that containers are handled in an efficient order and workloads between STS cranes are balanced. Control system algorithms are based on solutions used in real terminals. The modelled container vessel captures the geometry of a real 4,300 TEU container vessel.

Kinematics of STS cranes are described with a discrete time model and control system logics with a discrete event system model. The model is validated by simulating STS crane's discharging cycles and vessel discharging with a varying number of STS cranes. Simulation results are compared to literature. According to validations, the model can reproduce the behaviour of STS operations and produce reliable productivity estimates. The average productivity of simulated operations is around 30 moves per hour, if the cranes work without interferences. As the number of STS cranes increases, the number of interferences grow due to preserving of safety distances between cranes. Consequently, the productivity lowers and benefits gained by increasing the number of STS cranes decrease. Simulations suggest also that operational speeds of STS cranes impact greatly on operations' productivity. Consequently, a slight rise in operational speeds can enhance operations significantly.

Simulations revealed a minor fault in the implemented control system model. The distribution of workloads between STS cranes is not optimal, thus considerable deviations in workloads occur. In future, the algorithm should be enhanced to produce more balanced work distribution. In addition, a support for multi-lift spreaders should be added. For longer simulation periods, a feature that generates an arrival pattern for vessels should be implemented. Also, the number of vessel models should be increased to expand the number of simulation scenarios.

Keywords: STS crane, STS operations, modelling, simulation, productivity analysis

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

TIIVISTELMÄ

Jarno Koivula: Satamanosturioperaatioiden mallinnus ja simulointi tuottavuusanalyysiä varten
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Konttiliikenteen merkittävä kasvu on viime vuosikymmenten aikana johtanut yhä suurempien konttilaivojen käyttöön. Kasvavat konttivirrat vaativat konttiterminaalien logistiikalta tehokkaampaa toimintaa. Tässä diplomityössä luodaan simulointimalli satamanostureilla (STS-nostureilla) suoritettavasta laivojen purku- ja lastausoperaatioista (STS-operaatioista) MATLAB Simulink -ohjelmistolla. Mallin avulla voidaan suorittaa tuottavuusanalyysejä operaatioista erilaisilla nosturivariaatioilla ja tehdä johtopäätöksiä optimaalisesta konemäärästä ja -tyypistä. Malli laskee yksittäisten nostureiden tuottavuudet, tuottamattoman ajan sekä operaatioiden kokonaisajan. Tässä työssä suoritetaan herkkyysanalyysi STS-nostureiden määrän ja kinemaattisten parametrien vaikutuksesta operaatioiden tuottavuuteen.

Toteutetussa mallissa on mallinnettu STS-nostureiden kinematiikka, niiden ohjausjärjestelmä sekä yksi konttilaiva. Nosturit liikkuvat realistisesti ja liikenopeudet muuttuvat vallitsevien tuuliolosuhteiden sekä konttien painon mukaan. Mallinnetut nosturit on varustettu yhden kontin nostoon suunnitelluilla tarttujilla ja mallinnuksessa on huomioitu vierekkäisten nostureiden välillä ylläpidettävät turvavälit. Toteutettu ohjausjärjestelmä ohjaa STS-nostureita siten, että kontit käsitellään optimaalisessa järjestyksessä ja työmäärät nostureiden välillä ovat tasaiset. Toteutetut ohjausalgoritmit pohjautuvat olemassa olevien terminaalien ohjausjärjestelmissä käytettäviin ratkaisuihin. Mallinnettu konttilaiva perustuu todellisen keskisuuren konttilaivan geometriaan.

Työssä mallinnetaan STS-nosturin kinematiikka diskreettiaikaisella mallilla ja ohjausjärjestelmä asynkronisella sekvenssilogiikalla. Mallinnettu järjestelmä validoidaan simuloimalla STS-operaatioiden purkusyklejä ja vertaamalla saatuja tuloksia kirjallisuudessa esitettyihin arvoihin. Lisäksi laivan purkua simuloidaan vaihtelevalla nosturimäärällä ja saatuja tuottavuusarvoja verrataan kirjallisuuteen. Tulosten mukaan malli kykenee kuvaamaan STS-operaatioita realistisesti ja tuottamaan luotettavia tuloksia operaatioiden tehokkuudesta. STS-nostureiden työskennellessä häiriöittä, keskimääräinen tuottavuus on noin 30 siirtoa tunnissa. Nosturien lukumäärän lisääntyessä tuottavuus laskee, sillä häiriöiden määrä kasvaa turvaetäisyyksien ylläpitämisen takia. Tällöin nosturien lukumäärän lisäämisen hyödyt jäävät pienemmiksi. Simuloinnit indikoivat myös, että kinemaattisten parametrien vaikutus operaatioiden tuottavuuteen on suuri. Täten pienikin liikenopeuksien nosto saattaa parantaa tuottavuutta merkittävästi.

Simuloinnit paljastivat heikkouden implementoidussa ohjausjärjestelmässä. Työmäärien jako nostureiden kesken ei ole optimaalista, minkä vuoksi työmäärissä esiintyy suhteellisen suuria eroavaisuuksia. Tulevaisuudessa työnjakoalgoritmia tulisikin kehittää siten, että työmäärät jakautuisivat tasaisemmin. Lisäksi malliin tulisi lisätä tuki moderneille tarttujille, jotka mahdollistavat useamman kontin noston kerralla. Mikäli mallilla on tarpeellista simuloida pitkiä ajanjaksoja, olisi malliin syytä lisätä operoitavien laivojen saapumisaikoja generoiva ominaisuus. Lisäksi eri tyyppisten laivamallien määrää tulisi kasvattaa erilaisten simulointivariaatioiden lisäämiseksi.

Avainsanat: STS-nosturi, STS-operaatiot, mallinnus, simulointi, tuottavuusanalyysi

Tämän julkaisun alkuperäisyys on tarkastettu Turnitin OriginalityCheck –ohjelmalla.

PREFACE

This thesis was commissioned by Kalmar, part of Cargotec Finland Oy. From Kalmar, I would like to thank Hannu Santahuhta for providing me the topic and the opportunity to step into a new territory. In addition, I'd like to express my sincere gratitude to Johannes Mansikkala who supervised my work and provided valuable guidance during the process. From TUNI, I'd like to thank Matti Vilkko for examining the thesis and giving important academic insight to writing. I'm also grateful for Risto Ritala who agreed to work as a second examiner with a short notice. In addition, I'd like to thank my brother Tomi Koivula for helping me to check spelling and grammar.

The last six years in TUNI have been fulfilling and the time has passed quickly. I've gained lots of new friends and many unforgettable memories. Now that the studies are over it's time to turn the page and go out to work. I'd like to thank my whole family and my beloved girlfriend for precious support during these years.

In Tampere, on 30 October 2019

Jarno Koivula

CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

AGV	Automated Guided Vehicle
BAP	Berth Allocation Problem
CHE	Container Handling Equipment
DES	Discrete Event System
DFA	Deterministic Finite-state Automaton
HT	Horizontal Transportation
OOG	Out of Gauge cargo
QCAP	Quay Crane Assignment Problem
QCSP	Quay Crane Scheduling Problem
SC	Straddle Carrier
ShC	Shuttle Carrier
STS	Ship-To-Shore
TEU	Twenty-foot Equivalent Unit
TTU	Tractor-Trailer Unit
UDP	User Datagram Protocol

α	Interference exponent
mph	Moves per hour
q	Number of STS cranes

1. INTRODUCTION

A maritime container terminal is a large-scale system that takes care of container traffic between container vessels and hinterland transportation. Vessels arriving in a terminal moor at quayside berths, where containers are discharged and loaded by ship-to-shore cranes (STS cranes), the most common type of quay cranes. Discharged containers are transported to yard area and piled in stacks by stacking equipment. From the yard, the containers continue their journey to landside site for hinterland transportation or back to quayside for transshipping.

Container shipping has a significant role in cargo transportation. Today, over 17 % of world’s seaborne trade moves in containers when measured in weight. Moreover, 80 % of the volume of world’s merchandise trade is handled by ports. In 2017, the volume of global containerized trade was 148 million twenty-foot equivalent units (TEUs), while the annual increase was 6.4 %. The constantly growing trade has changed container shipping industry towards more consolidated form. During the past decade, shipping lines have merged and formed alliances when aiming for cost-savings with better fleet utilization. The shipping lines’ urge for better efficiency has led to adoption of larger vessels. Nowadays the largest vessels can carry over 21,000 TEUs. These mega-vessels usually sail on long-distance routes between transshipment hubs while smaller feeders handle the shorter routes. [2] The growth of vessel sizes has forced terminals to constantly aim for higher STS crane productivities and berth occupancy rates in order to keep themselves competitive. Still, shortages in crane and berth capacity are the major sources of vessels’ schedule issues. [33]

Container traffic in a single terminal can be several million TEUs per year [47]. Handling of such volume requires careful planning of terminal-level transportation. A lot of machinery is often involved in the logistics process, as hundreds of machines operate simultaneously in interaction with each other. This causes mutual interferences and makes it difficult to estimate the overall productivity of logistics and factors limiting the operations. To get a cutting edge on present-day sales business, terminal equipment manufacturers are investing in productivity simulations of complete container terminals. A terminal logistics simulation model establishes a way to examine operations’ efficiency with a specified machinery layout. Exact calculations of productivity rise are needed to assure customers of the benefits of machine upgrading. The analysis helps sales departments recognize bottlenecks of logistics and tailor product offerings to meet the customer demands. On the other hand, productivity analyses can help in product development or in planning of new terminals, since the efficiency of operations can be analyzed in advance.

As the logistics process is a complex system, modelling of a terminal for productivity simulations is not a straightforward task. The model must contain all container handling equipment (CHE) working on site in addition with their control systems. To get reliable results, all parts must be modelled with enough accuracy related to their real-life equivalents. Still, after the modelling part, simulations provide a swift way to generate productivity analyses. Adding a visualization to the model helps in debugging, makes observing of the operations easier and increases the model's value in marketing.

Kalmar, part of Cargotec Corporation, has been generating a comprehensive simulation model covering the whole terminal for productivity analyses. The model is built to be highly configurable to allow versatile use of the simulations. The number of machines working on site can be parametrized and the machines in addition with terminal control systems are modelled based on their real-life equivalents from the company's product family. The simulation model is created with MATLAB Simulink. Simulink's toolbox, called Stateflow, is utilized in modelling. Stateflow is designed for event-based modelling which supports combinatorial and sequential decision logic modelling [44]. Visualization for the model is set up with Unity, a game-engine widely used in software development.

In this thesis, a model of ship-to-shore operations (STS operations) is created. The model can later be integrated into the terminal-scale simulation model described above. STS operations cover the loading and discharging of containers onto/from container vessels with STS cranes. Modelling is done according to methods used in software development. The implemented model alone allows user to simulate STS operations with varying number of STS cranes and analyze the operations' productivity. The productivity is evaluated by measuring the turnaround time of vessels, i.e. the time required for STS operations, and the number of containers moved per hour by an STS crane. Also, the cranes' unproductive time is measured. The model is validated by comparing the simulated productivities and cranes' work cycle times to values found in literature. Without the simulation model, estimation of STS operations' efficiency would be extremely difficult. In this thesis, a sensitivity analysis is performed to study how STS cranes' quantity and kinematic parameters influence on operations' productivity.

Literature has proposed multiple models for STS operations [4-6, 11, 13, 22, 23, 25, 31]. The models are based either on optimization models or discrete event simulation models.

Optimization models are especially popular among studies examining optimization problems, such as optimal allocation of quay cranes and their workloads [5, 6, 22, 25, 31]. Discrete event simulation models are typically used in studies examining terminal operations in larger scale due to their ability to model modularity and enable visualization [4, 11, 13]. However, most of the discrete event simulation models proposed in literature are inaccessible to reader and lack the amount of detail. Quay crane operations are often modelled only with time estimates and their specific features along with vessels' features are neglected. In order to model STS operations realistically, the discrete event simulation models generated in this thesis consider the kinematics of STS cranes and utilize the geometry of a real container vessel.

The structure of this thesis can be divided into six parts. Chapter 2 introduces the theoretical background of maritime container terminals necessary for the reader to understand the factors influencing on STS operations and further to their modelling. The chapter provides the reader with a general overview of container shipping and terminal operations. A more detailed description of STS operations is presented in Chapter 3 where an STS crane, a container vessel and factors affecting to the operations' productivity are examined in close level. Chapter 4 discusses the theory related to STS operations' modelling and simulation and introduces typical modelling methods used in literature. The motivation for developing a new model is clarified and the framework for modelling is set. In Chapter 5, implementation of the model is described in addition with the software used in modelling and visualization. The specifics of the model along with the interfaces to upper-level systems are presented. In Chapter 6, the implemented model is validated through simulations by comparing the model's behavior to references found in literature. Discharging of the modelled vessel is simulated and a sensitivity analysis is performed to study the influence of STS cranes' quantity and kinematic parameters to operations' efficiency. Finally, conclusions and future research topics are presented in Chapter 7.

2. MARITIME CONTAINER TERMINAL

Maritime container terminals are hubs of international transportation networks. Their main task is to provide shipping lines efficient container handling services with short vessel turnaround times. Quay cranes discharge and load containers onto/from vessels while aiming for fast operation times. In terminals, containers are stored in stacks where they stay from hours to weeks. Approximately three quarters of the stacked containers continue their way to hinterland transportation whereas the rest are transshipped and continue their journey by sea [2].

This chapter provides a general overview of container shipping and maritime container terminals. Chapter 2.1 discusses the present state of container shipping. Chapter 2.2 presents the features of intermodal containers. Chapter 2.3 introduces maritime container terminal layouts. Chapter 2.4 discusses the options for container handling equipment (CHE) and Chapter 2.5 introduces the control systems used in terminals.

2.1 Container shipping

Container shipping is run by liner operators. They aim for financial success by providing customers diverse transportation networks and both short and reliable transit times. Currently, three global liner shipping alliances dominate the container trade. Their share of total deployed capacity in East-West route covers over 90 %. [2] Alliancing has allowed shipping lines to share their fleet capacity in order to fulfil the customer demands for comprehensive service networks. Demand for fleet capacity varies along with market conditions and seasonal changes. [30, 34]

The overall trend in vessel sizes has been growing. Today, the largest mega-vessels sailing on Asia-Europe route can carry over 21,000 TEUs [2]. The deepening and widening of essential maritime passages, for example Panama-canal, has allowed the adoption of larger vessels. The increase in vessel sizes has put pressure on terminals. A single port may not be able to discharge an entire vessel if asked because of the lack of handling capacity. This forces large vessels to call for several ports instead, which increases their round time. Other issues can also occur. Some ports may be inaccessible for example due to low bridges, tides or too small quay cranes. [30]

Container vessels follow a schedule with specific number of port calls and certain transit times. Planning of a vessel schedule is a difficult task as liner operators urge for high vessel utilization rates and customers for short transit times. Limiting the number of port calls shortens the transit times and consequently satisfies the customers, whereas supplementary port calls generate additional revenue to liner operators. Nowadays, routes where containers are transported through indirect routes via hubs are common, as they meet the demands of lower costs and higher vessel utilization rate set by liner operators. [33, 34]

Shippers favour exact timetables for delays can be costly. Missing a port call slightly during flood tide may cause a delay of several hours. Therefore, agreements between liner operators and terminals usually determine penalty costs for terminal operators if timetables do not hold [9]. Still, delays in container shipping are common. In 2006, only 53 % of vessel sailing on major routes were on-time [33]. Basically, causes of delays can be divided into four categories: terminal operations, port access, maritime passages and chance (mechanical failures, weather conditions etc.). The most common cause of delays is terminal operations. It is caused by queues in berths and the lack of handling capacity. In 2004, on East Asia – Europe route over 80 % of schedule issues were caused by terminal operations. The schedule issues have pushed liner operators to buy shares of key terminals to ensure immediate access to berths. [34] Buying of shares though requires large transportation volumes in order to be profitable [24].

2.2 Intermodal container

An intermodal container is a standardized steel box designed for efficient cargo transportation. Containers are basically steel boxes with standardized external dimensions allowing uniform handling regardless of the contents. Containers are mainly transported by sea, but other modes of transportation can be also used, such as trucks and trains.

Two ISO standards, ISO 668 and ISO 1161 define specifications for intermodal containers. Table 1 presents a few standardized container types. The most common types are 20 feet and 40 feet standard containers. The standard width and height are 8 feet and 8 feet 6 inches, respectively. Containers of 9 feet 6 inches high are referred as High-Cube containers [15]. Regardless of the size, all containers have equal corner fittings that allow lifting. Lifting can be performed with a special gripping device, called a spreader. Containers' structure allows stacking, which is essential for efficient transportation and storing. Stacking heights depend on weight restrictions set by container structure and stacking surface. The structure of 20 ft containers is firmer compared to 40 ft containers. Consequently, on a mixed stack 40 ft containers must always be on top. [30]

Table 1: *Intermodal containers specified in ISO 668 and ISO 1161 standards [15]*

ISO	**Length**		**Height**		**Width**		**Tare weight**	**Gross weight**
	ft	mm	ft	mm	ft	mm	kg	kg
1AA 1AAA	40'	12192	8'6" 9'6"	2591 2896	8'	2438	3800	30480
1CC	20'	6058	8'6"	2591	8'	2438	2300	30480
1EEE	45'	13716	9'6"	2896	8'	2438	4700	30480

Often container vessels transport cargo that need special treatment. Perishable goods are transported in reefer containers that are equipped with cooling systems. These containers are stacked in specific locations both on a vessel and on shore, where electric supply is available. Containers containing dangerous goods also require special attention and are similarly stacked in specific locations. Sometimes vessels transport goods that are oversized for standard containers, i.e. out of gauge cargo (OOG). OOG is transported in customized containers, for example in open top containers or flat racks, and needs to be handled with manually controlled equipment on shore. Break bulk cargo that cannot be containerized, called project cargo, requires also special handling procedures and manual handling. [9]

2.3 Terminal layout

A maritime container terminal can be divided into three different operational areas: quayside, yard and landside area. Quayside area starts from quay wall and reaches to container yard. It is responsible for STS operations. The operations include vessel discharging and loading with quay cranes in addition with container handover and horizontal transportation (HT) between quay cranes and yard area carried out by HT equipment. Yard area manages stacking of containers. The stacks function as a short-term storage for inbound and outbound containers waiting for later transportation. Stacking can be made by specific HT equipment or alternatively by yard cranes. Landside area includes a loading/discharging area for hinterland transportation, a container freight station, a gate to terminal area as well as an empty container storage and several other necessary facilities, such as office buildings. The discharging/loading from/onto hinterland transportation can be made by specific HT equipment or by yard cranes. Fig.1 presents the three operational areas. [9, 37]

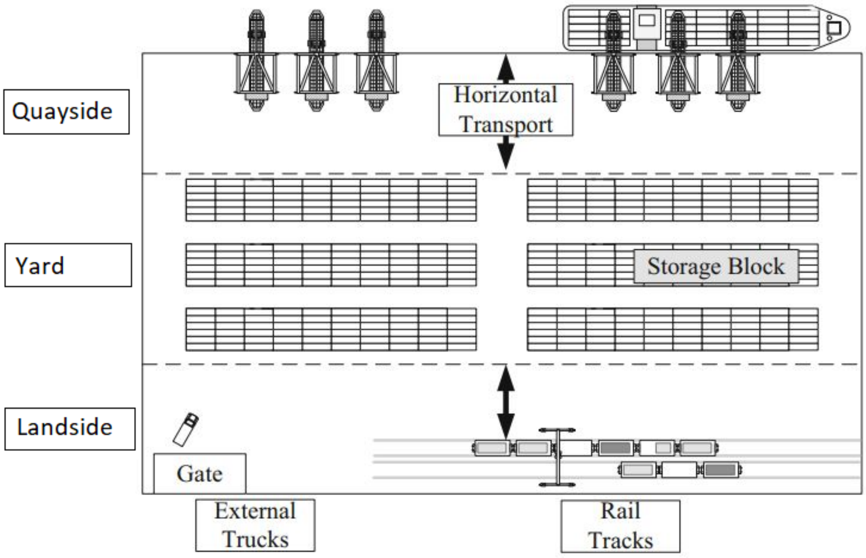
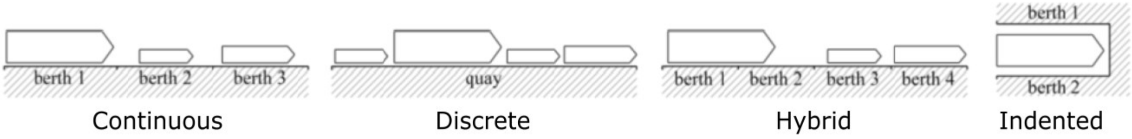


Figure 1: *General maritime container terminal layout. Adapted from [9]*

Vessels can be moored differently along quay wall depending on terminal's quay wall layout. Fig. 2 presents the different layout options. A discrete layout means that the quay wall is divided into several berths, where ships are directed and served separately. In a continuous layout the quay wall is not divided, and vessels can moor anywhere within the quay wall boundaries, given there is enough space. Hybrid layout is a combination of the two previous layouts. Discrete berths exist, but large vessels can occupy more than one berth. A special case of hybrid layout is an indented berth, where vessels are berthed between two opposite quay walls. This allows serving the vessels from both sides. In general, continuous layout allows more flexible STS crane assignment because cranes from one vessel can be directed to work on another vessel when needed. Also, terminal space utilization rate increases. [5, 6]



Continuous Discrete Hybrid Indented

Figure 2: *Different quay wall layouts. Adapted from [5]*

In yard area, stacks are usually arranged parallel or transversally to the quay wall in respect of container's longitudinal direction. In order to minimize travelling distances of HT equipment and maximize transportation efficiency, the stacks are located near quayside. The stacking area is divided into slots, each of which has a size of one TEU. Every slot has a certain logical position, that can be defined by three integer variables: bay, row and tier. Bay describes the slot's consecutive position in longitudinal direction and row in lateral direction. Tier informs the container's position in stack starting from the container on ground.

2.4 Container handling equipment

Handling of containers is performed with special container handling equipment. The types of CHE used in operations depend on many factors, but the main determinants are:

- Vessel sizes
- Container volume levels (annual and peak hours)
- Container dwell times
- Container types (number of different types and special containers)
- Costs (investment, maintenance and labour)
- Available land area (required stacking density and geographical constraints)
- Connections to hinterland transportation
- Compatibility with operation area and other equipment
- Environmental impacts (energy consumption and pollution) [9]

Mainly, vessel sizes and container volumes determine the size and number of quay cranes. Quay cranes and their throughput in addition with container dwell times further determine the number of HT equipment and yard cranes needed. Availability of land area normally sets the requirement for stacking density and stacking equipment. In high labour cost countries terminals prefer automated solutions over manual despite the higher investment costs. In recent years, environmental aspects have also become an important matter affecting to equipment decisions. [9]

Discharging and loading of containers from/onto ship is performed with quay cranes. In modern, medium-to-large-sized terminals, STS cranes are typically used because of their superior efficiency. Fig. 3 presents STS cranes. STS cranes are positioned on rail tracks parallel to quay wall on quayside area. STS cranes have a trolley moving horizontally between vessel and shore. The trolley has a hoist that is capable to vertical movement. The hoist is equipped with a spreader that allows the hoist to get a grip on container. STS crane can discharge containers when moving landwards and load containers when moving seawards. [9]

Figure 3: *STS cranes [32]*

While STS cranes have established their position on quayside, a variety of solutions have been created for HT between quay cranes and stacking area. HT can be performed by

- Reachstackers
- Straddle carriers (SCs)
- Tractor-trailer units (TTUs)
- Shuttle carriers (ShCs)
- Automated guided vehicles (AGVs)

Optimal solution for each terminal is different depending on the determinants described before. TTUs, ShCs and AGVs can perform only horizontal transportation while SCs can manage also stacking operations. Stacking with HT equipment, i.e. with reachstackers or with pure SCs leads to relatively low stacking density (350 – 750 TEU per hectare) because of the equipment's limited lifting capacity (maximum of 4-high). Stacking with SCs also requires a space between container rows which reduces stacking density. On the other hand, SCs can perform all stacking and transportation operations, including the loading of containers on trucks or trains. It is notable, that ShCs, SCs and reachstackers can pick and ground containers straight from/on the ground, whereas TTUs and AGVs need to be loaded and discharged by a crane. The feature eliminates the delays caused by loading/discharging operations, thus leading to better productivity. On the other hand, vehicles without the picking ability can move considerably faster. [9] Table 2 compiles the main features of HT equipment.

***Table 2:** Features of HT equipment*

HT equipment	Independent	Automatic	Picking ability	Stacking ability	Stacking density
Reachstacker	✓	✗	✓	✓	Low
SC	✓	✓	✓	✓	Medium
TTU	✗	✗	✗	✗	High*
ShC	✗	✓	✓	✗	High*
AGV	✗	✓	✗	✗	High*

** when combined with yard cranes*

When using HT equipment without the stacking ability, yard cranes, such as automated stacking cranes (ASCs), rubber-tyred gantry cranes (RTGs) or rail-mounted gantry cranes (RMGs) are used to perform the stacking. This is usually the case for high-throughput and high-density terminals. Yard cranes differ most in terms of interchange areas. ASCs' have interchange areas on both ends of stacks. Consequently, the whole area between ASCs' supporting legs, called portal, can be utilized in stacking. RTGs' interchange area is located between their portal legs, which reduces the available stacking area. Departing from the previously mentioned, RMGs have a cantilever that allows the interchange area to be located beyond the portal. Table 3 describes the typical features of the yard crane types. All of them can reach a stacking density of over 1000 TEUs per hectare [9]. ASC is considered as the most efficient type in terms of stacking density, although RMG and RTG follow close, respectively.

***Table 3:** Features of common yard crane types*

Yard equipment	Movement	Interchange area	Truck loading	Train loading
ASC	Rail tracks	On both ends	✓	✗
RTG	Rubber tyres	Between portal	✓	✓
RMG	Rail tracks	Beyond or between portal	✓	✓

The configuration of landside area depends heavily on hinterland transportation modes. Loading area for trucks is often integrated in the yard area and yard cranes or straddle carriers (SCs) manage the stacking. Loading area for trains is normally separated from the yard area in order to avoid crossing the train tracks. Yard cranes typically perform the train operations. [9]

In an automated terminal, HT equipment and yard cranes are usually automated while STS cranes still operate manually or remotely controlled. Of the HT equipment, SCs, ShCs and AGVs can be automated whereas TTUs and reachstackers work typically only manually. All types of yard cranes, ASCs, RTGs and RMGs can be automated.

Fig. 4 presents a schematic view of a logistics system with an STS crane, AGVs, RMGs and both truck and train transportation. Generally, the choice of type and number of CHE is case-specific and while all equipment can be delivered with different sizes and capacities, and some of them automated, the number of options is broad. The optimal solution is dependent of terminal operator’s emphasis on different criterion. Basically, the minimum number of HT equipment is defined by rush hours, for the delays on quayside should be eliminated. The fact that shipping lines favour the ports that are capable of fast operation, terminals’ time and volume requirements typically arise from the quayside. In order to gain a high vessel handling efficiency, all areas must be well synchronized together. This means that the quay cranes must be able to work at maximum rate without any delays caused by other equipment. [9] The root of productivity simulations lies in the task of finding a balance between transportation efficiency and costs.

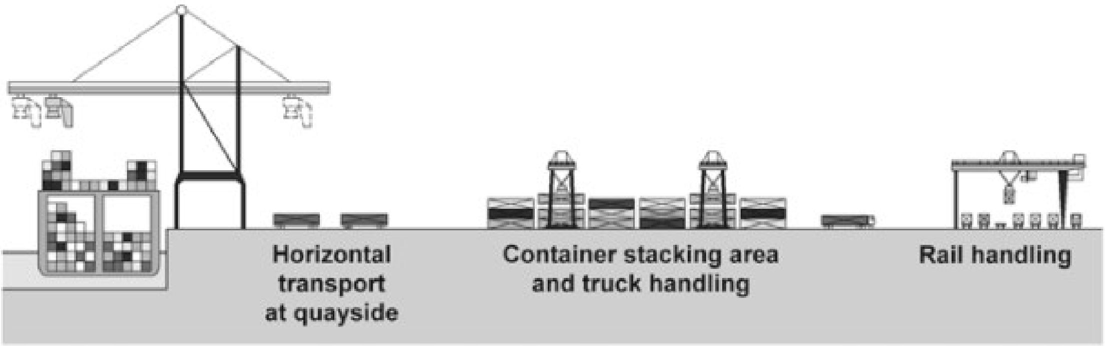


Figure 4: *Logistics system where HT is performed with AGVs and stacking with RMGs [9]*

2.5 Control systems

In a container terminal, the number of CHE working simultaneously can vary from tens to several hundreds. Regardless of the size, every terminal requires a powerful control system to ensure efficient and synchronized performance of operations. Terminal operating system (TOS), the heart of terminal operations, is a software application that supports terminal planners in operation planning, equipment scheduling and control, invoicing and gate management. The system possesses information of all containers within a terminal. [7, 8]

Prior to vessel or hinterland transportation arrival, terminal planners are given a timetable of arrival and departure times along with a list of containers to be loaded and discharged. Based on the information, the planners determine in cooperation with TOS the optimal number of equipment deployed, the equipment’s work schedules and containers’ destinations. The number of decisions to be made in fast pace is large. TOS helps planners to make fast decisions with little human errors and match operational requirements. The efficiency of terminal is strongly dependent of the quality of TOS and the interaction between the system and terminal planners. [8]

During last decades, TOS has evolved from a decision supporting tool into a real-time control system. A modern TOS can have several advanced features. It can manage container movement by controlling CHE in real-time so the CHE's utilization rate is maximized while travel distances and maintenance, labour and fuel costs are minimized. TOS can also optimize the stacking strategy of yard area for more efficient space utilization and lesser stack reshuffling. Furthermore, vessel stowage plans can be made automatically. [32]

TOS is an upper-level system that manages logistics process and financial functions. To connect TOS to the physical equipment, a separate software is usually used. [28] Fleet management system (FMS) works as a translator between TOS and CHE's automation systems. It monitors CHE and executes the tasks assigned by TOS. FMS converts the movement tasks sent by TOS into exact routes that automated vehicles can execute. The routes are designed in a way that no collisions or deadlocks occur. FMS also manages error and warning handling. Fig. 5 presents the structure of container terminal's control system. FMS and TOS can run on a same server. The communication between FMS and CHE is performed with wireless network or cable. [42]

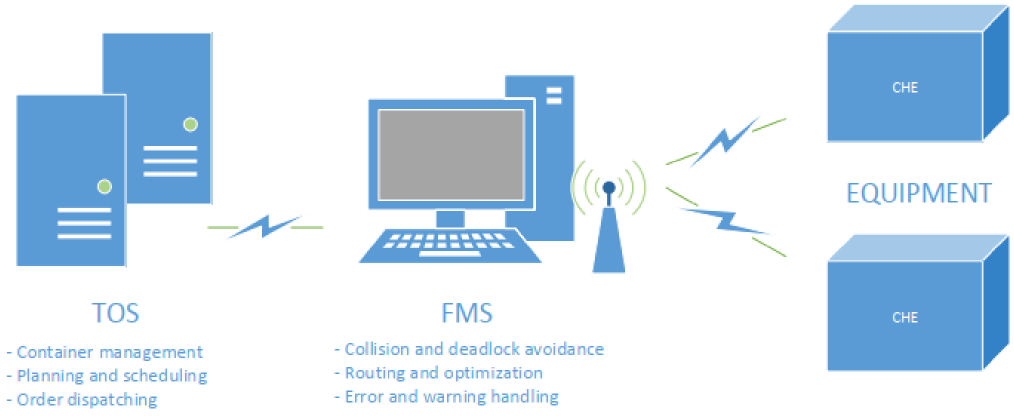


Figure 5: *Container terminal's control system [42]*

Usually in FMS, machines of certain type are divided into groups based on their working area. The groups are controlled by separate control systems. For example, a single control system can be responsible of all STS cranes working on a single berth. The system takes care of all controlling actions, i.e. the monitoring and the routing, for the equipment under its control. Routing is done via space reservations. When generating a route for a specific equipment, the control system makes a space reservation that allows only the machine in question to move in the reserved space [28].

3. SHIP-TO-SHORE OPERATIONS

Ship-to-shore operations are performed on quayside. The term covers discharging and loading operations of vessels with STS cranes, container handovers and horizontal transportations between the cranes and yard area. As STS cranes operate directly with the vessels, their contribution to terminal's productivity is significant. This chapter describes the STS operations in detail. Chapter 3.1 presents the basic structure and operation of an STS crane. Chapter 3.2 describes a container vessel and its cargo hold structure. Chapter 3.3 discusses the factors influencing on both terminal's and quayside's productivity.

3.1 Ship-to-shore crane

An STS crane is a crane capable of serving container vessels. The basic design of STS cranes has remained the same from the early 1960s, although sizes and lifting capacities have increased. Nowadays, the largest STS cranes can lift over 120 tons while having an outreach of over 70 m and a lifting height of 50 m. Lifting speed at rated load can reach 2.5 m/s. [9, 33]

Fig. 6 shows the basic structure of an STS crane. The crane's body is made of steel and a portal frame forms the crane's load-bearing structure. [49] An STS crane has three movement axes. Portal legs are mounted with wheels that allow the gantry to move in line with quay wall on rail tracks. A trolley is attached to horizontally positioned main boom. It can move along the boom transversal to quay wall. Trolley has a hoist that can move vertically. A spreader that allows container picking is attached to the hoist.

The area between rail tracks is known as portal and the area outside the tracks on landside is called backreach. Containers can be handed to HT under portal or backreach, depending on terminal design and HT equipment used. [9] Machinery house, called ehouse, is located on top of the boom, usually above the portal leg closer to backreach. Crane movement is powered by electric motors that get their power via cable/busbar. The crane is operated manually from driver's cabin which is attached to trolley and moves together with it. In recent years, semi-automated STS cranes have become available. They don't have a driver's cabin at all for they can be driven remotely from operation room on ground level. [26]

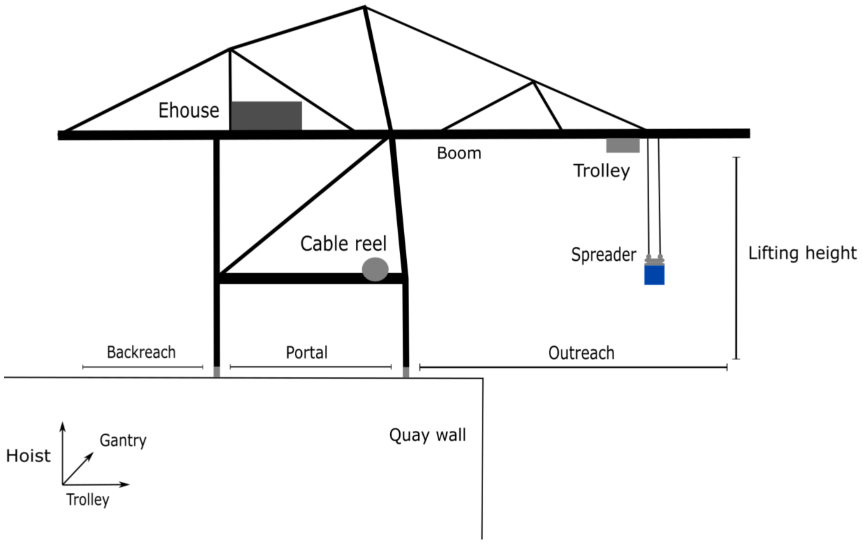


Figure 6: *Structure of a ship-to-shore crane*

Several STS cranes can work simultaneously on a single vessel. Working next to each other is possible given the vessel is long enough for cranes to have enough room to operate. As the cranes operate on same rail tracks, a minimum safety distance must be maintained during operations. Increasing the number of cranes quickens the operation, but too many cranes per vessel can cause interferences between adjacent cranes, thus leading to lower productivity.

Operation of a single STS crane requires a lot of manpower. Besides an operator, a foreman who coordinates the operations and stevedores for lashing operations are needed. Before the actual container operations, after vessel has berthed, lashing crew is lifted onto the vessel in a lashing cage to remove lashings from containers one by one. Lashing bars and turnbuckles are removed, and twist locks are unlocked (see Chapter 3.2). The crew stores the loose lashings into vessel's gear bins. The gear bins are transported to quayside and stored near the handover area for the time of container operations. During the container operations, stevedores remove the twist locks from discharged containers and correspondingly fit them to the containers to be loaded. [9, 35]

The actual discharging/loading operations consist of the following steps:

- Containers on deck are discharged
- Hatch covers separating containers on deck and in hold are lifted aside
- Containers in hold are discharged
- Containers are loaded in hold
- Hatch covers are placed back
- Containers are loaded on deck [23]

When the loading operations start, stevedores begin to perform lashing operations on vessel. After all containers are loaded, the lashing is checked by the vessel crew, after which the vessel is ready to set sail.

Discharging and loading of containers consists of repeated work cycles. While discharging, the operator drives trolley above a container on a vessel, lowers the hoist, picks the container, assures the spreader is locked and lifts the container. The trolley is moved to container handover area under portal or backreach where the container is grounded on top of a HT vehicle or on ground. This cycle is repeated until all containers are discharged. When loading, the cycle is performed vice-versa, i.e. the containers are moved from container handover area onto the vessel. Fig. 7 illustrates the work cycle of vessel discharging.

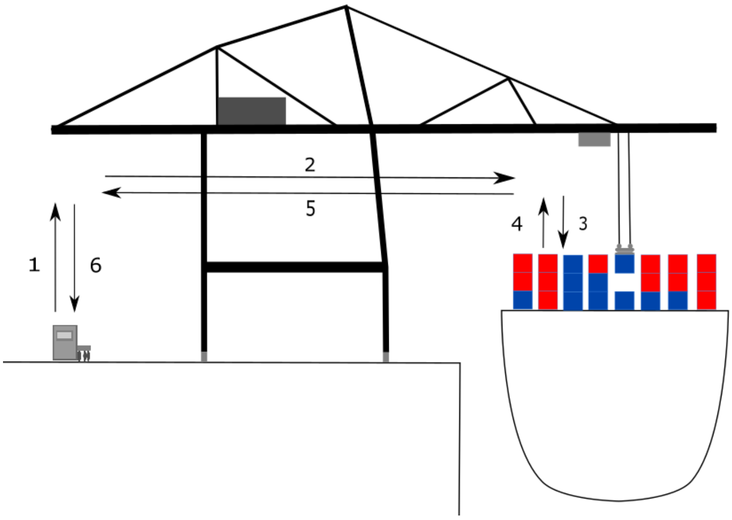


Figure 7: *Work cycle of vessel discharging*

The cycle discussed above defines the basic operation of an STS crane, called single cycling. Alternatively, STS cranes can be operated on a double cycling mode. Double cycling means that discharging and loading operations are combined. When an STS crane heads towards vessel to discharge a container, it picks another container from shore and loads it onto the vessel. In this way, idle movement of the crane is eliminated and transformed into productive work. Double cycling also reduces idle movement of HT equipment between quayside and yard area. HT equipment can transport a container for inbound and outbound at the same trip. Using double cycling reduces the amount of operational cycles leading to faster operation and smaller fuel consumption. However, double cycling requires more operational planning, for STS cranes' schedules must consider more complex loading and discharging orders. Fig. 8 illustrates double cycling operation. [27]

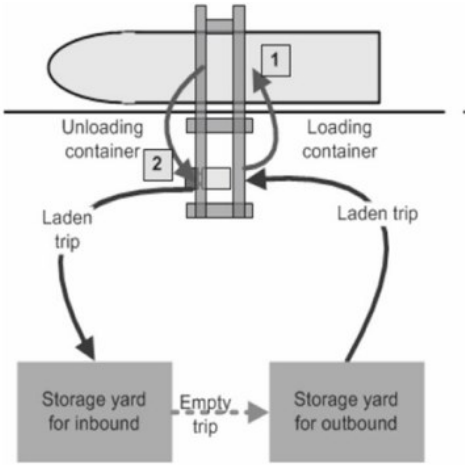


Figure 8: *Double cycling operation [22]*

Besides single-trolley cranes, double-trolley cranes have also been developed. A double-trolley crane has two separate trolleys operating independently. One of the trolleys moves containers from a vessel onto a special coning platform located in portal, while the other one takes care of the transportation between the platform and HT equipment. This way the trolley interacting with the vessel won't be exposed to delays caused by HT equipment. [9, 23] The latter trolley can be fully automatized, but the one interacting with the vessel more complex to automate and will most likely remain manually operated in near future as well. Fig. 9 presents an example of STS crane portal with a coning platform. Discharged containers are grounded on the platform, from where the second trolley picks and moves them to container handover area in backreach. With or without the double-trolley, portal can function as a temporary storage for hatch covers and OOG/project cargo. In addition, a space for access road is reserved to ensure fluent access to quay wall. [9]

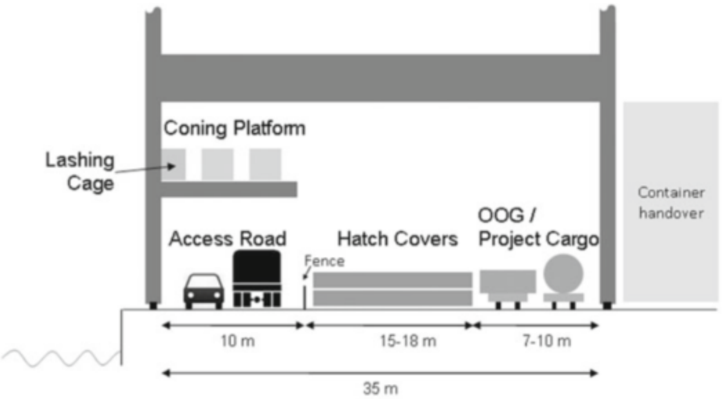
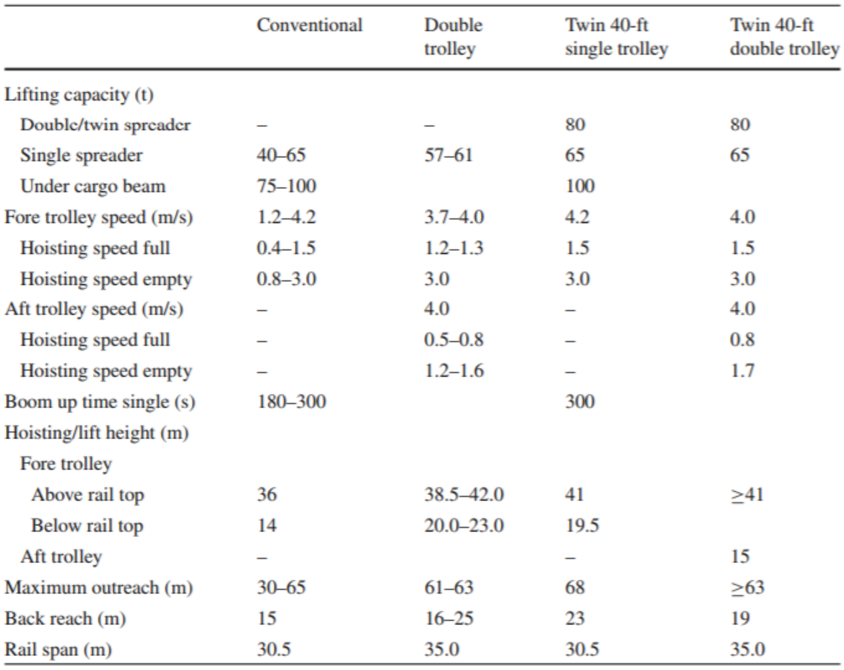


Figure 9: *Portal of STS crane [9]*

Several types of spreader combinations have been developed. A conventional STS crane has a single-lift spreader capable of lifting either a single 20 ft or 40 ft container. Spreader length can be set to the corresponding length before picking. More modern spreader type is a twin-lift spreader. Twin-lift spreader's special structure allows to lift two 20 ft containers at the same time, given the two containers are located close to each other. [13] Tandem-lift spreaders are representing a new type of spreaders that are built to further increase operations' productivity. The spreader consists of two trolleys moving together that are both equipped with twin-lift spreaders. As a result, the spreader can lift four 20 ft containers at the same time. Alternatively, the tandem-lift spreader can lift either two 40 ft containers or two 20 ft containers and a 40 ft container. Theoretically tandem-lift operations can double the operation productivity by cutting the amount of lifting cycles by half when comparing to twin-lift spreaders. In practice this doesn't happen though, for all lifting operations cannot be planned for tandem-lift spreaders. However, it is possible to change the tandem-lift spreader to twin-lift spreader during operation. The change takes time approximately for 90 seconds. Currently, the operators using tandem-lift spreaders set the target ratio for tandem-lift operations to 20-30 % while the operators using twin-lift spreaders set the ratio to 100 % when all containers are 20 ft. [13, 23] However, the entire cargo rarely consists only of 20 ft containers.

Table 4 presents technical specifications of STS cranes. The table includes information of lifting capacities and heights as well as external dimensions and operational speeds. Twin 40-ft single and double trolleys in Table 4 refer to STS cranes equipped with tandem-lift spreaders. Gantry speed information is excluded from the table. The top speed for gantry is approximately 1,2 m/s with an acceleration between 0.1 – 0.3 m/s^2 [3].

Table 4: *STS cranes' technical specifications [43]*



	Conventional	Double trolley	Twin 40-ft single trolley	Twin 40-ft double trolley
Lifting capacity (t)				
Double/twin spreader	–	–	80	80
Single spreader	40–65	57–61	65	65
Under cargo beam	75–100		100	
Fore trolley speed (m/s)	1.2–4.2	3.7–4.0	4.2	4.0
Hoisting speed full	0.4–1.5	1.2–1.3	1.5	1.5
Hoisting speed empty	0.8–3.0	3.0	3.0	3.0
Aft trolley speed (m/s)	–	4.0	–	4.0
Hoisting speed full	–	0.5–0.8	–	0.8
Hoisting speed empty	–	1.2–1.6	–	1.7
Boom up time single (s)	180–300		300	
Hoisting/lift height (m)				
Fore trolley				
Above rail top	36	38.5–42.0	41	≥41
Below rail top	14	20.0–23.0	19.5	
Aft trolley	–		–	15
Maximum outreach (m)	30–65	61–63	68	≥63
Back reach (m)	15	16–25	23	19
Rail span (m)	30.5	35.0	30.5	35.0

STS cranes can be divided into three types based on their size: Panamax, Post-Panamax and Super Post-Panamax. A Panamax STS crane can serve vessels with 11-13 rows while their outreach is 30-40 meters. Post-Panamax cranes have an outreach of 45-55 meters and can serve vessels with 17-19 rows. The largest STS cranes, i.e. the Super Post-Panamax cranes can serve the largest vessels with 21-23 rows. Their maximum outreach is 60-70 meters. [3]

3.2 Container vessel

Vessels used in container shipping are specially designed for container transportation. They are designed with a principle of maximizing cargo capacity and vessel controllability while minimizing fuel consumption and emissions. [30]

A cargo area of a container vessel can be divided into two separate areas: hold and deck. Containers in hold are stacked on fixed structures whereas containers above deck are stacked on top of liftable hatch covers. Both areas can be further divided into separate container slots. Every slot has a logical position which can be addressed with bay, row and tier indexes. Bay information refers to slot's position in longitudinal direction starting from vessel's bow. Row indexing refers to slot's position in transversal direction while tier indexing indicates the slot's position in a stack. Fig. 10 presents a schematic view of a vessel cargo area along with logical positioning of slots.

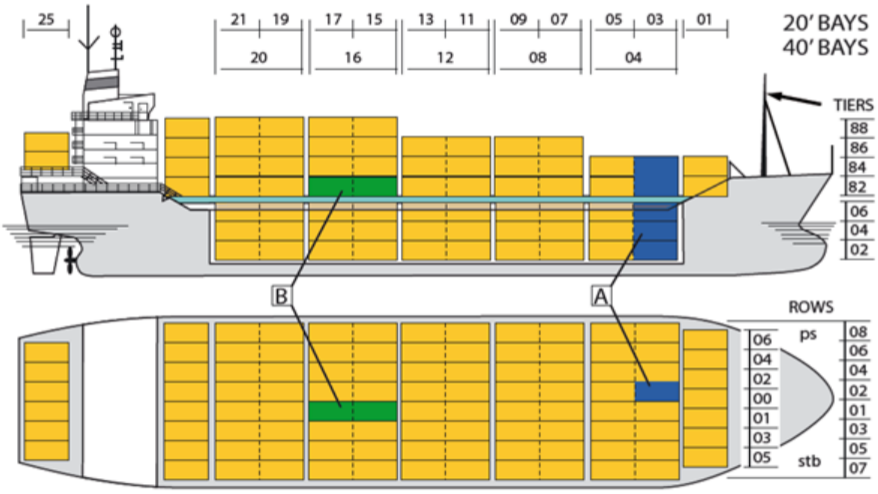


Figure 10: *Example of container vessel's cargo area structure and slot positioning [15]*

As can be seen from Fig. 10, bay indexing usually starts from one. Odd bay indexes refer to 20 ft container slots while even indexes refer to 40 ft slots. Typically, two consecutive odd slots represent the same physical location as an even slot between them. Consequently, a 40 ft slot can contain a 40 ft container of alternatively two 20 ft containers. In the latter case, the 20 ft containers are referred with odd bay indexes. Row indexing starts either from zero or one. If a slot exists on the vessel's centre line, the slot's row index is zero. If there isn't a slot exactly in the middle of the vessel, indexing starts from one. Slots on starboard are addressed with odd row indexes while slots on portside are addressed with even indexes. Tier indexing in hold starts from two and grows always by two while on deck the indexing starts from 82 and grows with the same principle. Sometimes, if the stacks are high, the indexing above deck starts from 72 to avoid situations where indexes rise above 100. [15, 23, 30]

Container stacks on a vessel expose to several types of harmful movement caused by vessel motion and environment (sea conditions, wind and green seas). To eliminate the movement of container stacks and to assure cargo safety, special lashing equipment is used to keep containers together. Cells guides, hatch covers, lashing bridges, container fittings, container stanchions and a special lashing software form the lashing system. [15] The main parts of a lashing system are illustrated in Fig. 11.

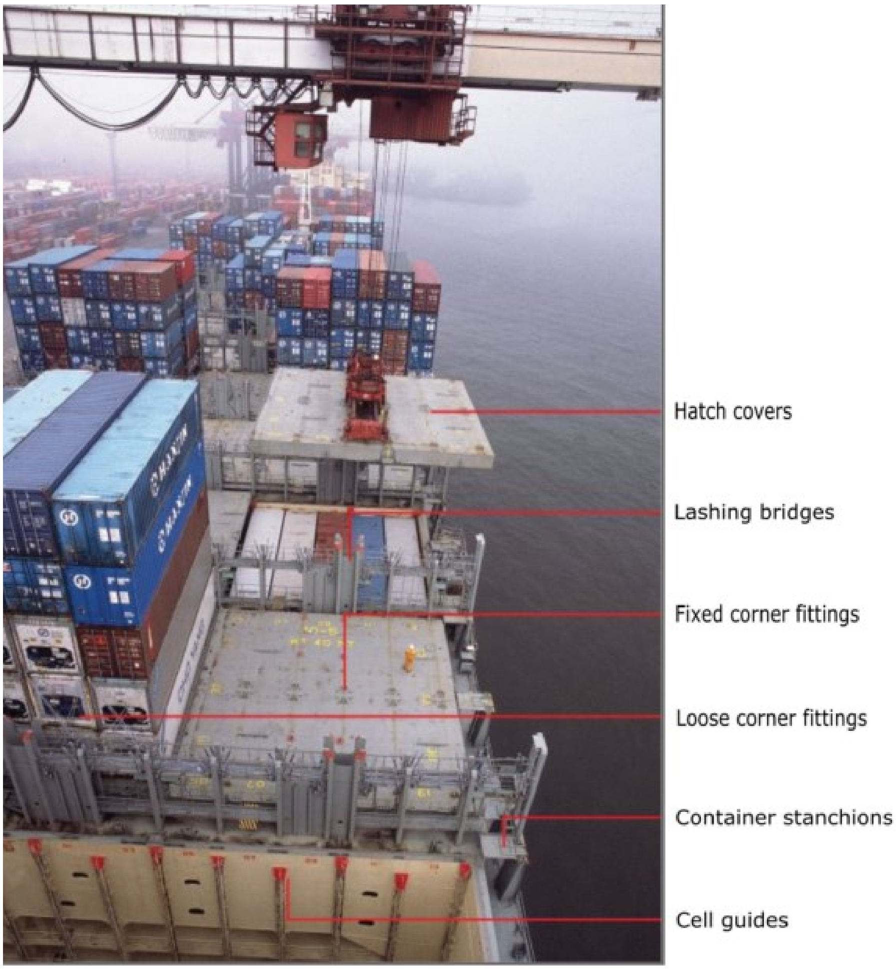


Figure 11: *Lashing system. Adapted from [15]*

Cell guides keep containers tightly positioned in hold. Liftable hatch covers separate the hold from deck and enable container stacking above deck. Lashing bridges that resemble the cell guides support the stacks on deck. Lashing bridges typically reach up to four tiers high. Besides the lashing bridges, loose container fittings such as twist locks, lashing bars and turnbuckles, are used to secure containers on deck. Twist locks are small locks that can be placed on containers' bottom corner castings to secure them to the containers below. Lashing bars and turnbuckles attach container piles to fixed structures such as lashing bridges or hatch covers. Fixed corner fittings provide attaching points for the containers in lowest tiers. Container stanchions allow the extension of vessel beam and consequently increase the cargo capacity. A special lashing software is used to calculate lashing forces based on actual cargo profile. The software ensures before departure that the lashings are sufficient and the stability of the vessel is acceptable. [15]

Twist locks prevent containers in a stack from collapsing. Therefore, before a container can be lifted from a stack, its twist locks must be unlocked. When the twist locks are unlocked, they move along with the container and engage automatically if the container is grounded on top of another container or a HT vehicle. However, if the container is lowered on ground (that is the case sometimes in STS operations), the twist locks must be removed. Stevedores remove the twist locks manually on quayside. STS crane operator stops the hoist just before the container hits the ground and waits until the stevedores remove the twist locks. The procedure is opposite for loading: stevedores install the twist locks on a container heading to vessel deck right after the container has lift off. [35]

When a vessel arrives in a terminal, it is first berthed with the help of pilots and tugs. Berthing takes approximately 15-30 minutes [13, 50]. After stevedores have removed lashings, container operations can start. A couple hours before the arrival, terminal operator is given a list of containers to be loaded and discharged on/from the vessel [31]. Based on the list given, a stowage plan is created by a terminal planner in cooperation with a central planner working for liner operator and a vessel crew. Stowage is performed according to the stowage plan that defines the order of container operations. In order to maximise the efficiency of the transportation and minimize transit times of vessels, stowage plans should minimize lifting work and at the same time consider following port calls by making containers heading to next port easily accessible. Stowage plan must make a compromise between fast loading and vessel utilization while at the same time consider lashing forces. When obtaining the plan, communication with vessel crew is critical to consider all details, such as: [1, 30, 40]

- Containers must be loaded so that the stability of the vessel remains good during and after the operation. Usually containers heading for a certain port are placed wide longitudinally in order to ensure efficient discharging (enough space for multiple STS cranes to operate).
- Weight restrictions are considered by maximum stack weights and with a certain stacking order. 20 ft containers are always loaded on the bottom of the stack while 40 ft containers are on top. Limits for stack weights depend on the type and position of a stack. Above deck, hatch covers define the limits. Weight limit for a 20 ft stack above deck is 90 + 90 tonnes, while the limit for a 40 ft stack is around 180-210 tonnes and 240 tonnes for a mixed stack.
- The aft and forward have less structure-supporting water underneath them due to vessel geometry. This must be considered in stowage plan with appropriate stack weights.
- Lashing forces exerting to fixed structures (hatch covers and foundations) and containers must be below limits. Containers' structure is usually the weakest link. To avoid stack collapse, containers are supported with loose container fittings. The use of lashing bridges reduces the amount of support needed.
- Special types of containers, such as reefer or hazardous containers must be placed in specific locations (where for example a power supply is provided).

Usually a single STS crane operates at a certain bay until all containers marked in a stowage plan on that bay are transferred. This makes the operation more efficient because the time needed for gantry movements is minimized. Minimizing the number of all movements and the overall travel distance leads not only to a greater productivity but also to lesser interferences between STS cranes. For small feeder ships, efficiency of operations is lower, because cranes must change bay more often [9].

3.3 Productivity

Productivity of a container terminal depends on multiple different factors. While terminals can differ a lot in their size and layout, no standard method exists to determine their overall productivity. Operators tend to emphasize different factors when developing terminals. Traffic forecasts, area availability, size and depth of waterways, labour costs and hinterland transportation modes amongst others influence on decisions. All these factors eventually become visible in machinery layout. Busy main-hub ports with small available area in high labour cost countries prefer more expensive CHE with high automation level, handling capacity and stacking density while smaller ports in low labour cost countries with low traffic may prefer manually operated, cheaper small-scale CHE. In order to function efficiently, all parts of the system including machinery and control systems, must be well synchronized. [9] In the end, the overall productivity of a terminal is determined by the bottleneck resource i.e. the part of operation that prevents the system from functioning more efficiently [13].

As the STS cranes are in straight interaction with vessels, the efficiency of ship-to-shore operations is the most critical phase in terminal operations. When considering the overall terminal productivity, the term *terminal capacity* is often used. It defines the number of containers (or TEUs) discharged or loaded by STS cranes per year i.e. the *annual quayside throughput*. Sometimes the throughput can be expressed as the annual throughput per quay wall meter. Terminal capacity is often heavily dependent on vessel sizes. Handling of large vessels is more efficient because of larger cargo capacity and lesser number of required gantry movements. Therefore, the value of throughput is significantly affected by customer type and should not be looked upon as an absolute measure. [9] Table 5 shows the annual throughputs of ten largest container ports in the world during 2012-2016. As can be seen, all of them are in Asia. Apart from few exceptions, the overall trend in trade volume is growing.

***Table 5:** Annual throughput of world's largest container ports [47]*

Rank	Port	Annual throughput (Million TEU)				
		2016	**2015**	**2014**	**2013**	**2012**
1	Shanghai, China	37.13	36.54	35.29	33.62	32.53
2	Singapore	30.90	30.92	33.87	32.60	31.65
3	Shenzhen, China	23.97	24.20	24.03	23.28	22.94
4	Ningbo-Zhoushan, China	21.60	20.63	19.45	17.33	16.83
5	Busan, South Korea	19.85	19.45	18.65	17.69	17.04
6	Hong Kong, China	19.81	20.07	22.23	22.35	23.12
7	Guangzhou Harbor, China	18.85	17.22	16.16	15.31	14.74
8	Qingdao, China	18.01	17.47	16.62	15.52	14.50
9	Jebel Ali, United Arab Emirates	15.73	15.60	15.25	13.64	13.30
10	Tianjin, China	14.49	14.11	14.05	13.01	12.30

When considering the productivity of STS operations, the most used measures are *moves per hour* (mph) and vessel *turnaround time.* The first refers to the number of boxes or TEUs moved per hour. The productivity of a single STS crane is often reported this way. [9, 13] The second measure defines the time a vessel stays berthed at a terminal i.e. the time taken to finish the STS operations. [22, 23, 31].

Factors influencing on quayside efficiency are presented in Fig.12. As can be seen, four major influences can be distinguished:

- Environmental influences
- Handling demand
- Infrastructure capabilities
- Terminal capabilities

Environmental influences such as tides and wind, water traffic and customs matters can cause delays that take effect before the actual STS operation. Especially large vessels with high draft may regularly encounter situations where they must wait for high tide. Handling demand refers to effects caused by vessel features. Vessel's features define how many berths it occupies, how many containers must be handled, how much time it takes to moor, how large safety distance must be kept between berthed vessels etc. Also, vessels' arrival rate impact greatly on operations' efficiency, for delays in arrival can cause considerable rush at the quayside. Infrastructure capabilities set the restrictions for berths and their capabilities. Some berths may not have enough depth for larger vessels with high draft. Terminal capabilities, such as the number of quay cranes and HT equipment available in addition with the stacking capacity and traveling distances also affect to operations' efficiency. [9]

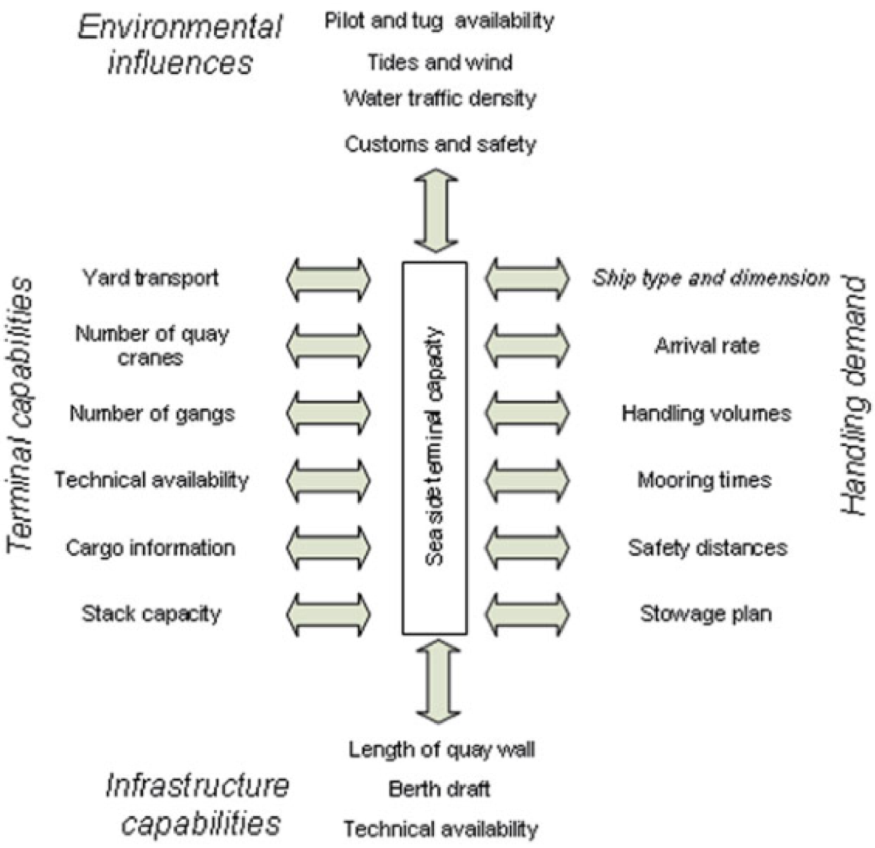


Figure 12: *Factors affecting to quayside capacity [9]*

The productivity of a single STS crane is determined by mechanical and operational aspects. Theoretical productivity is determined by mechanical factors, such as spreader type and movement speeds. The actual productivity is affected by many operational factors. For example, stowage plan, waiting times for HT equipment, interferences with adjacent cranes, weather conditions and unproductive times such as lunch breaks, shift changes, hatch covers, possible spreader changes and driver skill levels in addition with machine breakdowns all affect to the actual productivity. [9, 13, 23]

In literature, three main operational problems influencing on quayside productivity are recognized and broadly studied [5, 6, 37]. They are

- Berth allocation problem (BAP)
- Quay crane assignment problem (QCAP)
- Quay crane scheduling problem (QCSP)

BAP deals with the problem how to instruct a set of vessels to correct positions at quay wall at the right time in order to ensure efficient operation. Terminals have different strategies when making berth allocation. Some may serve vessels with a first-come, first-served basis while others may favour large vessels ahead in the queue regardless of the arrival time. On the other hand, some berths may be owned by shipping lines which makes them privileged and some may be suitable only for certain vessels due to draft and machinery restrictions. Usually the best operation efficiency is achieved when the transportation distance between the berth and container yard is minimized. [6, 25]

QCAP deals with the question how many quay cranes to assign per vessel. On a single vessel level, quay cranes should be assigned so that the turnaround time of a vessel is minimized. On a quay wall level, total crane capacity should be divided between vessels so that the overall efficiency of quayside is maximized. STS crane availability, maximum number of cranes per vessel, type and volume of containers in addition with quay wall layout affect to decisions. On discrete layout every berth has a fixed number of STS cranes that work only for the berth they belong to. In continuous layout, STS cranes can be moved along the quay wall which allows operators to divide the available capacity better. This increases the efficiency of STS operations and allows cranes to be assigned from one vessel to another during operation. When assigning cranes, it should be noted that increasing the number of cranes doesn’t necessarily lead to better efficiency for the interferences increase between adjacent cranes. [5, 31]

QCSP considers the task of dividing the discharging/loading operations defined in a stowage plan evenly between STS cranes and determining the scheduled processing sequences for the cranes. This means that the discharging and loading order is defined in a way that minimizes the overall operation time while avoiding interferences between adjacent cranes. Number of movements and their distances, idle times and differences in cranes’ workloads should all be minimized. [31]

The methods used in literature to solve BAP, QCAP and QCSP are discussed in Chapter 4.2.1. In recent years, more studies that combine the three problems have been published. Combining the problems aims at shorter vessel turnaround times, for the bottlenecks in the yard and in HT can be reduced for example by combining BAP and storage yard allocation problems. Also, the planning process of stowage plan should be done together with QCSP in order to guarantee productive STS crane operations. [6]

4. TERMINAL PRODUCTIVITY SIMULATIONS

Simulations have become an important part of planning in container terminal business. Simulators allow users to simulate systems with different inputs and configuration parameters in a virtual world without interacting with the real system [9]. Container terminal simulators provide a way to evaluate the dynamic processes of container terminals and analyse the statistics of operations (productivities, idle times, number of moves etc.). Simulators are used to examine the logistics' efficiency in advance when planning new or extending existing terminals. Issues such as capacity extensions, new scheduling algorithms or alternative stacking strategies can be tested in means of simulation. [21]

A Finnish CHE manufacturer Kalmar has created a simulation model of container terminal's logistics process for productivity analysis. In this thesis, a comprehensive model of STS operations is created that can be integrated into the terminal-scale model. This chapter clarifies the need for a new model and provides the reader a necessary background of modelling and simulation to understand the implementation of the STS operations model described in next chapter. Chapter 4.1 describes systems, models and simulation in general. Chapter 4.2 discusses the published literature considering the modelling and simulation of STS operations. Chapter 4.3 states the motivation for generating a new model and Chapter 4.4 defines the modelling methods used in this thesis.

4.1 Systems, models and simulation

To understand modelling and simulation, it is necessary to introduce the term *system*. One way to define a system is to call it *a combination of different components interacting with each other in a way that produces some functionality*. The functionality wouldn't be the same if one of the components was removed. Systems are usually associated with physical objects and natural laws, although systems describing for example human behaviour and population dynamics also exist. [12] In this thesis, attention is focused on the former type.

Systems can be classified based on their behaviour. Output of a static system is independent of past input values. The output changes exactly at the same moment when the input is changed. A dynamic system is the opposite, for its past input values determine the output values. This means that the manipulation of dynamic system's input values cannot be seen immediately, for the change of output takes some time. Most of the systems in nature are dynamic, for they involve quantities such as temperature, pressure, acceleration and speed. These quantities are continuous variables evolving over time. [12, 36]

A model tries to duplicate system's behaviour. It is an abstraction of a real system consisting of a set of mathematical equations describing the relations between system components. A model enables a way to predict the system outputs when it is excited with specific inputs. Simulation means evaluation of the system model numerically. The data gained from simulations can be used to estimate various quantities of interest. Above all, simulation models are tools for engineers to analyse systems and develop control and performance measurement techniques for them. By using simulation models, tests can be performed without the actual system with desired input functions and model parameters. This is often much more cost-efficient when compared to tests with the actual system, especially if the system is highly complex or physically large. [12]

4.1.1 Dynamic models

Basically, models of dynamic systems can be made in two ways. Modelling can rely on physical relations and balance equations or alternatively on measurements from the real system. Usually the modelling process combines both ways. Modelling with physical relations and balance equations is based on elementary principles, such as mass and energy balance as well as force and torque balance [36]. To model a system from measurements, a set of measurable variables associated with the system must be defined. Part of the variables are selected to function as input data. The variables are varied and measured over time. At the same time, the other variables, i.e. output variables, are also measured. Finding the mathematical relation between input and output data produces the model. It should be noted that models are always only approximates of systems' real behaviour, for it is extremely difficult to model any system perfectly. Therefore, models should always be verified and validated properly to ensure their suitability for purpose. [12]

When creating a model, modeller should decide what features of the real system are of interest. Unimportant features should be left outside the model and essential features should be included [29]. The inputs and outputs should be selected based on the modeller's interests. For example, when modelling a combustion engine, some may be interested in the relation between air-fuel mixture and piston movement and consequently model the combustion process and cylinder geometry very accurately. Others may be more interested in the interaction between the driver and the vehicle's acceleration. In this case, the engine can be modelled more broad-mindedly neglecting combustion phenomena and concentrating on the relation between throttle pedal and acceleration. [36]

Dynamic models can be divided into several different types. Three main types are

- Continuous time models
- Discrete time models
- Sequential models

Continuous time models are described by linear or non-linear differential equations. They give quantitative descriptions of mass, energy, force or momentum balances. Discrete time models are described by linear or non-linear difference equations. In discrete time models, the information is available only at specified discrete time instants. Computers work sequentially in time and use sampling to transform continuous time data into discrete time. The choice of sampling time is a part of modelling. Sequential models describe sequential systems that are often found in industrial processes and control logics. Usually sequential systems have discrete inputs and outputs with on/off type binary values. [36] Modelling in this thesis concentrates mostly on sequential systems. Therefore, sequential systems and models are examined in more detail below.

Sequential systems can be divided further into two types: combinatorial and sequencing networks. Combinatorial network's binary output condition depends on several input conditions that must be satisfied simultaneously. The system has no memory or *states*, i.e. the conditions of inputs are checked always at present time. This makes combinatorial systems static systems. An example of this kind of a system is a process computer that checks all input conditions have a correct value before turning the machine on. Sequencing network has a memory (states) and therefore it presents a dynamic system. Sequencing network's output depends on both present and previous values of inputs or states. A state can be defined in the following way: *A state of a system at a specific time instant describes the behaviour of a system at that exact time instant in some measurable way* [12]. A sequencing network model consists of finite number of states. Only one state can be active at a time. An active state is a result of preceding events or user interactions. The transition between states can be either asynchronous or synchronous. Asynchronous or event-based state transition means the change of state is triggered by logical conditions whereas a synchronous or time-based state transition means the transition is triggered by a clock pulse. Usually many industrial processes are asynchronous. [36] Asynchronous sequencing network system is also known as discrete event system (DES).

4.1.2 State machines

Discrete event systems can be described with state machines. A state machine, or an automaton, is a device that describes the logical behaviour of DES via state transition diagram. If the automaton has a finite number of states, it is called deterministic finite-state automaton (DFA). An example of DFA's state transition diagram is presented in Fig. 13. [12]

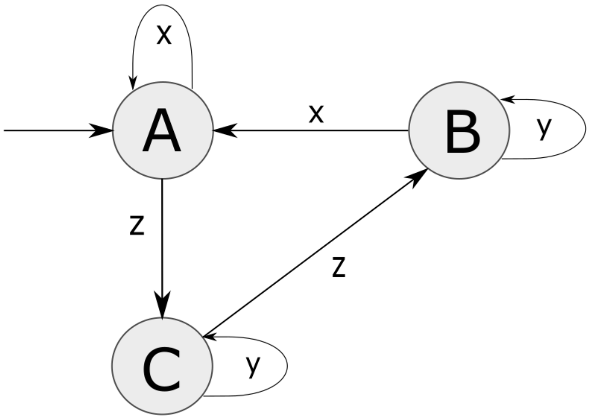


Figure 13: *State transition diagram of DFA*

The state diagram presented in Fig. 13 has three states, *A, B* and *C* and three possible events *X, Y* and *Z*. The events can be generated spontaneously by the modelled system itself or they can be external inputs. In state diagrams, the initial state is indicated with an empty arrow. In this case, the initial state is *A*. If the system is at state *A* and an event *X* occurs, a transition happens, but it doesn't change the state. Similarly, event *Y* won't change the state. However, if an event *Z* takes place while state *A* is active, a transition from *A* to *C* happens and C becomes the active state. Correspondingly, if *C* is active, event Z causes a transition from *C* to *B* but events *Y* or X won't change the active state. While *B* is the active state, only event *X* can change the state from *B* to *A*. Depending on the modelled system, state transition diagrams can vary significantly in terms of states and transition relations. States can contain information that change for example the system's output or some local variable when the state becomes active. Similarly, transitions can contain functions that change variables when activated.

In many cases, systems include both time-driven and event-driven dynamics. These kinds of systems are called hybrid systems. A hybrid system can be modelled using both event-based and time-based models. An example of a hybrid system is a batch process where tanks are filled with liquid to a certain level. Fluid flow has time-driven dynamics. It is modelled with a continuous time model and the filling process is controlled with a continuous time controller. Changing of tanks is an event-driven process that is modelled as DES and controlled with event-based logics. [12]

4.2 Modelling methods used in literature

Basically, two different model types are used in literature to model container terminal operations: optimization models and discrete event simulation models. Both model types and related literature are discussed below.

4.2.1 Optimization models

Deterministic and stochastic optimization models schematize terminal operations through single queue models or with a network of queues. The models are often quite complex and therefore used to model relatively small systems. [11] Optimization models are typically used to solve optimization problems, such as BAP, QCAP and QCSP (see Chapter 3.3).

Literature has proposed several different algorithms to solve BAP. Most of the solutions are heuristic because of the problem’s NP-hardness. Approximately 40 % of the solutions use Genetic or Evolutionary algorithms. Usually the optimization models aim to minimize vessel turnaround times. The optimal solution of BAP depends on quay wall layout, arrival rates of vessels and working times of STS cranes. Some studies consider discrete quay wall layouts, some continuous and others hybrid. Arrival rates are also dealt differently among models. Some consider only vessels currently waiting to be berthed while others include also vessels scheduled to arrive later. The way how STS cranes’ working times are determined varies too. Working times can be defined as fixed numbers or as variables depending on stochastic distributions or vessel’s berthing positions. In addition, some models determine the working times from cranes’ quantity or their schedules. In other words, the working times are integrated to QCAP or QCSP. [6]

The optimization models considering QCSP can be divided into three groups based on the task allocation algorithms they use: bay, cluster and single container -based algorithms. Bay-based algorithms allocate individual bays to STS cranes. All containers in the allocated bays must be processed by the same crane. Cluster-based algorithms allocate groups of containers in adjacent locations to the cranes. No complete bays are assigned. Single container -based solutions assign single containers, as the name suggests. All approaches have their advantages. Bay-based algorithms are considered the simplest because of larger allocation units. Cluster-based algorithms and single container-based algorithms are more complex due to smaller allocation units. On the other hand, they can provide more balanced workload especially in situations where the number of containers to be handled varies a lot between bays. [31, 22]

Over 80 % of the proposed QCSP optimization models use heuristic methods and almost 30 % of these are Genetic or Evolutionary algorithms. The models aim to minimize vessel turnaround time. Algorithms consider the cranes' initial positions, work cycle times and the time spent for gantry movement. Operational restrictions such as non-crossing constraints and safety distances between cranes are also considered. [6, 22, 31] Studies imply that allowing only unidirectional gantry movement from bow to stern or vice versa won't worsen the quality of solution significantly. Instead, it reduces the amount of possible solution and hence improves the computing time. [31, 22]

The surveys made by Meisel and Bierwirth [5, 6] provide a comprehensive review of the literature considering BAP, QCAP and QCSP. There is a great number of studies considering all three problems. Still, targets for development can be found. When considering BAP, there is a need for uniform benchmark where different solutions can be compared. Also, many of the current BAP algorithms lack liner schedules, which is a relevant matter in practise. Studies about QCSP lack the use of stochastic evaluation in container handling times. This means the crane work cycle times, waiting times for HT and stochastic events such as breakdowns of CHE are not considered properly. Also, the stability of a vessel during STS operations is usually neglected. [6]

4.2.2 Discrete event simulation models

Discrete event simulation models provide a less complex approach for modelling when compared to optimization models. They describe terminal characteristics in a more realistic way, make results more understandable by enabling visualization and allow the user to play with different scenarios. With discrete event models, it is possible to use modularity. Terminal operations consist of a finite number of working machines and control systems and have a clear hierarchy. The modular nature of terminal operations makes discrete event approach a natural choice. Discrete event simulation models can be divided into two classes: macroscopic and microscopic models. The former describes the movement of an "aggregation" of containers, while the latter considers the movement of each container by estimating the times of the handling operations or by modelling the movement. [11]

In literature, many discrete event simulation models have been implemented. Bielli et al. [4] modelled the macroscopic behaviour of a terminal to evaluate policies generated by control systems. The discrete event simulation model was implemented with Java and based on estimated mean values of operations' durations. STS operations were modelled with mean time values describing the time needed to move a container from vessel to HT equipment and vice versa. Exact values were not presented.

Carteni and Luca [11] studied the microscopic modelling of a container terminal locating in Italy. The implemented simulator was made with Witness and it modelled different container handling operations with stochastic estimates of the operations' duration. The estimates were based on data gathered from the real terminal. Mean values of durations were identified, probability distribution functions calibrated and compared, and different estimation methods investigated. The implemented model considered different types (20 ft and 40 ft) and weights of containers and included single-lift and twin-lift operations. However, the quay cranes modelled were mobile harbour cranes instead of STS cranes.

Yang et al. [13] studied the productivity of STS cranes equipped with twin-lift and tandem-lift spreaders. Theoretical productivity, measured as boxes per hour, for both spreader types was calculated based on STS cranes' mechanical specification (spreader type and kinematics). The productivity was then compared to operational productivity produced with simulations. A discrete-event terminal-scale simulation model consisting of four discrete berths was created with Plant Simulator 8.1. The model included STS cranes, HT equipment and yard cranes. Exchange of containers between HT equipment (TTUs) and STS cranes was modelled along with STS cranes' kinematics. However, the model excluded lifting of hatch covers, possible machine failures, lunch breaks, change of shifts, weather conditions and operators' skill levels.

Huang and Li [23] studied the performance of tandem-lift spreader operations. HT equipment and yard cranes were excluded from the simulations. STS operations were modelled more precisely than in the last-mentioned, for lifting of hatch covers and delays caused by spreader changes were included. Actual stowage plans were used in simulations. The simulation software used was not mentioned in the study. Containers were discharged and loaded based on an algorithm developed for QCSP. The simulation experiments were made with 19 vessels by using four to six STS cranes.

Models of STS operations proposed in literature often lack the amount of detail. Exact parameter values are not presented, and without an exception the models are inaccessible to reader. STS cranes' behaviour is typically modelled only with time estimates. Moreover, the estimates used are usually deterministic. Those studies that use stochastic estimates don't consider different container types or lifting heights [11]. The lack of studies simulating the kinematics of STS cranes is apparent. This is somewhat problematic, for the vessels' geometries and STS cranes' features such as maximum operational speeds affect considerably to STS operations. Often vessel types are not specified accurately, even though serving an ocean-going vessel is completely different from serving a small feeder due to differences in vessel geometries. Other shortcomings in literature are apparent too. Interferences between adjacent cranes are seldom considered and the impacts of different wind speeds and container weights on cranes' kinematics are often neglected.

4.3 Motivation for developing a new model

Kalmar has been generating a microscopic discrete event simulation model of a container terminal covering all terminal operations. The model includes a visualization for real-time movement of containers and CHE. The model enables a swift way to simulate terminal operations with different machinery and area layouts, and consequently detect the factors affecting productivity. Productivity analyses can be utilized in many ways. For example, sales departments can use them to tailor product offerings. Simulation results indicating a significant rise in productivity with upgraded CHE can be highly important in bargaining. On the other hand, terminal planners can use the model to test different terminal layouts or CHE designers can examine the logistics' efficiency with customized parameters. Adding a visualization to the simulation model makes observing of the operations easier and increases the model's usability in marketing as visually appealing simulations can be presented to customers. On the other hand, visualization helps in modelling as the implemented parts can be debugged easily.

The goal of the modelling is to implement a highly configurable simulation model of a container terminal. This is important, for the model should be adaptable to correspond customers' terminals. Duplication of real-life layouts allows a case-specific examination of logistics' efficiency. To serve Kalmar's purposes, the modelling focuses on productivity of CHE and includes the essential parts of control systems (i.e. TOS).

In this thesis, a model of STS operations is created. The implemented model is to be integrated to the terminal-scale model later. Therefore, the architecture and the interfaces need to imitate the terminal-scale model. A quay wall consisting of eight discrete berths should be modelled, each of which can have a maximum of eight STS cranes. The model of STS crane will be based on a single-trolley STS crane equipped with a single-lift spreader. The crane's kinematics are to be modelled with a discrete time model whereas control logics should be modelled with a discrete event simulation model. Consequently, the system to be modelled is a hybrid system.

The model of STS operations must consider all essential factors affecting to STS operations' productivity. All relevant vessel, container and STS crane features along with control systems are to be modelled. The vessel model will be based on a real vessel geometry and include hatch covers. The most common container types (20 ft and 40 ft) should be modelled in terms of external dimensions and weights. The STS crane model must consider the kinematics of gantry, trolley and hoist. The kinematics should change according to wind circumstances and container weights. The model should produce movement paths that are smooth and consider obstacles. In addition, interferences between adjacent cranes need to be considered and the control systems must replicate Kalmar's real control systems. Configuration of parameters should be effortless and their adjustment range wide.

4.4 Framework for modelling process

Creation of a simulation model requires careful planning. A clear strategy for modelling is necessary to ensure explicit progress of the work. Software development industry has created multiple methods for software development that aim to enhance the development projects' controllability, quality and productivity. The methods can be adapted to several fields of engineering, including modelling. According to a widely known and used waterfall model developed by Winston Royce in 1970, the process of software development includes the following phases that are executed step by step:

- Requirements analysis
- System design
- Implementation
- Testing
- Maintenance [38]

Requirements analysis defines the software requirements, i.e. what the software should do and how to do it. System design specifies data structures, software architecture, interfaces and the logic behind the functions in algorithmic detail. The actual implementation takes place after the requirements analysis and system design, after which the software is tested. In testing, the software's functionality is ensured, and possible bugs are searched and fixed. The maintenance phase starts after handing over the software to a customer. It includes fixing of bugs and updating the software according to customer's needs. [38]

The waterfall model resembles noticeably of the modelling cycle presented in [9]. The modelling cycle consists of the following steps:

- Analysis and specification of the problem
- Generation of the model
- Model validation
- Testing
- Analysis of the actual situation and definition of the bottlenecks
- Creation, modelling and experimentation with the alternative solutions
- Drawing conclusions and decision making [9, p. 87]

The first phase of the modelling cycle corresponds to requirement analysis and system design in waterfall model. Generation of the model is equal to implementation whereas model validation, experimentation and analysis of the actual situation, including alternative solutions, are part of testing. The maintenance part of waterfall model is neglected in the modelling cycle, for models are often used by their creators in decision making and not handed over to customers.

As the waterfall model is an established practise in software development industry, its framework is used in this thesis to outline the modelling process. Maintenance phase is excluded from this study.

5. MODELLING OF SHIP-TO-SHORE OPERATIONS

In this chapter, the modelling process of STS operations is described thoroughly. Chapter 5.1 presents the software used in modelling, simulation and visualization. Following chapters describe the modelling process with reference to the phases of waterfall model. Chapter 5.2 specifies the model requirements whereas Chapter 5.3 presents the system design. Chapter 5.4 describes the actual modelling process. The testing phase is partitioned into its own section and is presented in Chapter 6.

5.1 Software

The software used for modelling and simulation is MATLAB Simulink. It is a widely used graphical programming environment for model-based design and multidomain simulation generated by MathWorks. Simulink can be used to model algorithms and physical systems using block diagrams. Block diagrams are graphical representations of a system via input-output blocks [29, p. 419]. The software allows user to generate hierarchical models that consist of several sub-systems. This enables explicit partitioning of the modelled system into logical sub-systems. [41]

Simulink's toolbox, called Stateflow, is used along with Simulink to implement the simulation model. Stateflow is designed for event-based modelling which supports combinatorial and sequential decision logic modelling. Stateflow models can be simulated as a block within a Simulink model. With Stateflow, it is possible to develop, inter alia, task scheduling, fault management and supervisory control logics. [44] Stateflow combines hierarchical state-machine diagrams with traditional flowchart diagrams. It is generally used in hybrid systems to capture the interaction of event-driven and time-driven dynamics. Event-driven discrete systems (for example control systems) can be modelled with Stateflow whereas time-driven continuous dynamics (for example machine kinematics) are modelled with other Simulink tools. [20, 41]

A visualization for the model is set up with Unity, a cross-platform game-engine widely used in game development and lately more and more in engineering. The visualization is run concurrently with the simulation. Concurrent visualization means that animation is being displayed simultaneously with the simulation, whereas in post-processed visualization the graphics are displayed after the actual simulation calculations [7].

5.2 Requirements analysis

Requirements analysis transforms stakeholder's needs into discrete requirements. Requirements can be divided to two different classes: functional and non-functional requirements. Functional requirements define what kind of functional features the desired software should have, i.e. what kind of outputs the system should produce with specific inputs. More plainly, functional requirements describe *what* the software should do. Non-functional requirements define the software's general features. They set the constraints how functional requirements are implemented. That is, non-functional requirements describe *how* the software will do what it is meant to do. Examples of non-functional requirements are software's performance and external interface requirements, design constraints, and software's quality attributes. Often, when developing an embedded system, upper-level system defines the non-functional requirements. [20, 38]

Both the functional and non-functional requirements of STS operations' modelling are presented in Table 6. The requirements partly touch the matters presented in Chapter 4.3. The requirements arise from Kalmar that pursues highly configurable and easy-to-use model that produces reliable results with visually appealing appearance. The model should also be easy to integrate into terminal-scale model.

Table 6: *Functional and non-functional requirements for the simulation model*

Requirements	
Functional (what the model should do?)	**Non-functional (how it is done?)**
Model STS operations at discrete berths realistically.	STS cranes' kinematics (kinetics is not considered), control systems and interferences with adjacent cranes are modelled (hybrid system). Vessel model is generated based on a real vessel geometry. Hatch covers are included. 20 ft and 40 ft containers are modelled.
Include a real-time visualization of STS operations.	MATLAB is used in modelling and Unity is used in visualization. The model produces real-time coordinates of crane movements that are used in concurred visualization.
Be user-friendly also to people without simulation background.	Simulation parameters are configured in a single Extensible Markup Language (XML) file that is easy to understand and use.
Present productivity measures to user.	Vessel operation time, STS cranes' productivities and idle times are calculated and presented to user.

Include widely configurable layout in terms of area and machinery.	The number of discrete berths and STS cranes per berth is configurable (max. 8 for both). Origins of berths in terminal coordinates addition with STS crane parameters are configurable.
Be integrable into terminal-scale model.	Architecture and interfaces of the model are designed to correspond terminal-scale model. Model initialization and structure follow the same procedures as other models.
Run multiple times faster than real-time	Data structures and algorithms used are chosen in a way that computational times are minimized.

5.3 System design

System design is the second phase of waterfall model. Its purpose is to specify software architecture, interfaces, data structures and logics behind the functions in algorithmic detail. [38]

5.3.1 Architecture and interfaces

Architecture of the implemented model follows the structure presented in Fig. 14. The architecture design is adopted from the terminal-scale model. Sub-models of operations simulation manager (OSM), terminal operating system (TOS), fleet management systems (FMSs) and CHE form the hierarchical main model. An interface to visualization is integrated into the TOS model.

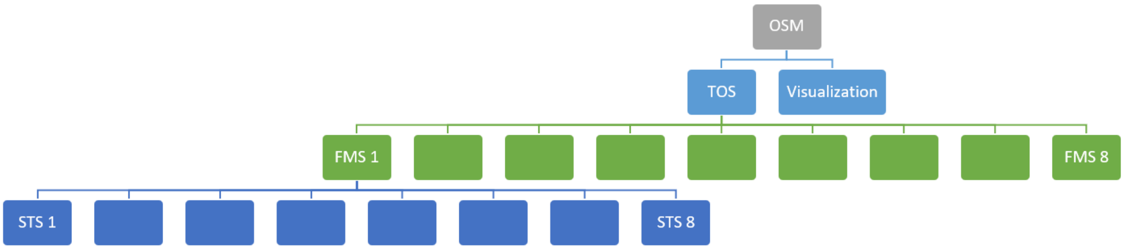


Figure 14: *Model architecture*

OSM locates in the topmost layer. It functions as an interface between user and the simulation model. User configures the parameters that define the simulation scenario in an XML document (see Chapter 5.3.2). OSM layer reads the configuration file and transforms the parameters into a Simulink-compatible form. Vessel model is also defined in OSM.

TOS and an interface to visualization form the second layer. The interface to visualization performs communication between the Simulink model and Unity via User Datagram Protocol (UDP). TOS takes care of container and hatch cover generation and manages job creation. Jobs are defined as tasks telling the cranes where to move and whether to pick or ground a container. Job sequences are generated with the principle of maximizing operations efficiency (see Chapter 3.3 about QCSP). Productivity values are measured and presented to user in this layer.

Each berth has its own FMS that controls the berth's STS cranes. FMSs handle the jobs sent by TOS. They transform the movement jobs into exact routes that contain the exact paths for movement and send the routes to corresponding STS cranes. The paths are computed in a way that collisions with obstacles, such as other containers, are avoided. FMSs also monitor cranes under their control. If an STS crane receives a job that is inconsistent with adjacent STS cranes, i.e. the job isn't executable without crossing of cranes, FMS assigns the adjacent crane a new job that orders it to move out of the way.

STS cranes form the lowest layer. Along with the vessel model, they are the only models that describe physical objects. STS cranes follow the route instructions sent by FMSs. The cranes pick and ground containers until all jobs assigned to them are finished. STS crane models include kinematics that imitate the movement of real STS cranes. Kinetics is not included. STS cranes' position and spreader status information are gathered and sent to visualization concurrently.

5.3.2 Data structures and algorithms

The model handles a large amount of data and therefore efficient data structures are required. Simulink supports the use of buses in data transfer within and in between models. A bus is a name-based hierarchical structure of signals. A bus is composed of several signals, called elements. The elements can be of any type, including buses themselves (creating a nested bus structure). The use of buses reduces visual complexity in a model as multiple signals can be bundled into a single bus. A bus can have an associated bus object, that contains the architectural properties of the bus, such as the number and order of elements, and the elements' hierarchy and data types. Bus objects are used to validate bus signals and they don't include element values. If a bus element linked to a bus object doesn't match with the bus object's definition, MATLAB generates an error message. [48] The model utilizes buses and bus objects in all data transfer between and within its sub-models.

All persistent data of the model is saved in a data dictionary. Data dictionary is a data repository that defines parameters and signals related to a model [51]. All models that are linked to the same data dictionary have access to the information saved in it. Multi-dimensional arrays are used to save information of all container slots. All containers and their properties generated by TOS are saved in a list. The jobs generated by TOS are sent to FMSs and saved in temporary queues. The routes generated by FMSs are sent to STS cranes and similarly saved in queues. The routing algorithm implemented was based on a simple rule of obtaining always an adequate safety distance to obstacles and circling them from above (see Chapter 5.4.4).

Lookup tables are used to determine velocities and accelerations of crane movements in STS crane model. The kinematic values are changing according to wind speed and container weights. In addition, multiple modular functions were implemented to calculate mathematical operations that are needed on a regular basis. The use of modular functions simplifies the model.

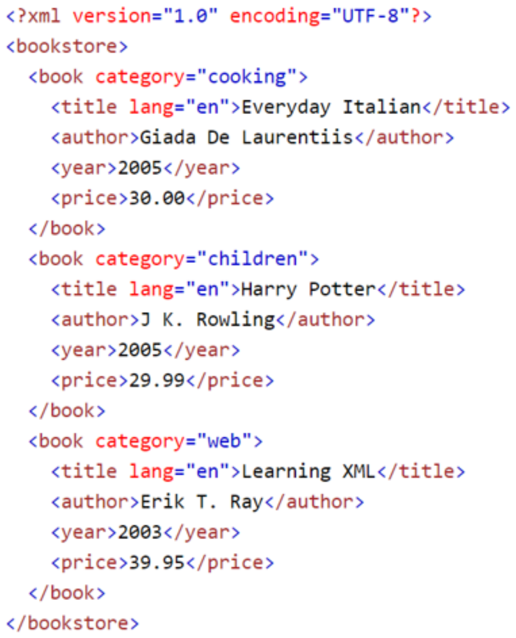
The vessel model, visualization and parameter configuration utilize Extensible Markup Language (XML) data type. XML is a data type developed in 1996 by World Wide Web Consortium (W3C). It is a simple and flexible text format widely used in data transfer and storing. XML stores all data in plain text format which makes the data highly compatible between different systems. XML document structure is based on a tree structure that starts at a root element and branches to child elements. The structure includes the following elements:

- a prolog
- a root element
- child elements
- sub-child elements [52]

Prolog defines XML version and character encoding and is always typed on the first line of an XML document. The following lines including root, child and sub-child elements define the actual content. In XML document, all elements are typed inside angle brackets. The ending of element’s influence is indicated by retyping the element’s name with an additional slash character before the name. Elements are typed on intended lines based on their hierarchy in the tree structure.

Every element can have child elements. The child elements can further have their own child elements, i.e. sub-child elements. Elements can have attributes that specify their features. The attributes are typed right after the elements and their values are typed inside quotation marks. Elements’ values can be typed straight between element names without any punctuation marks.

Fig. 15 presents an example of an XML document. The example considers a bookstore and it lists information of all books on sale. Fig. 16 describes the tree structure and relates it to the example.



```
<?xml version="1.0" encoding="UTF-8"?>
<bookstore>
  <book category="cooking">
    <title lang="en">Everyday Italian</title>
    <author>Giada De Laurentiis</author>
    <year>2005</year>
    <price>30.00</price>
  </book>
  <book category="children">
    <title lang="en">Harry Potter</title>
    <author>J K. Rowling</author>
    <year>2005</year>
    <price>29.99</price>
  </book>
  <book category="web">
    <title lang="en">Learning XML</title>
    <author>Erik T. Ray</author>
    <year>2003</year>
    <price>39.95</price>
  </book>
</bookstore>
```

Figure 15: *Example of an XML document [52]*

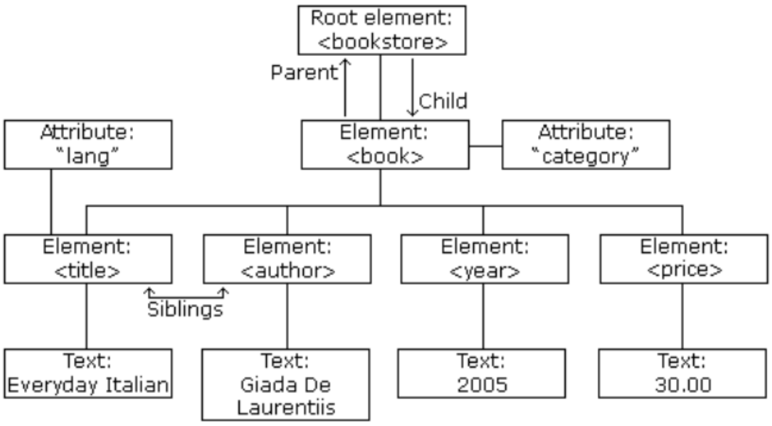


Figure 16: *Tree structure of XML document [52]*

The example has a root element called “bookstore”. It is typed on the second line and retyped at the end and so it’s influence reaches till the end where the element’s name appear again. The root element has one child element called “book”. The child element has an attribute, that defines the book’s category. The child element has multiple own child elements, i.e. sub-child elements. The sub-child elements are named as “title”, “author”,”year” and ”price”. Also, the sub-child element “title” has an attribute that specifies the languge of the book. Elements’ values can be typed straight between element names without any punctuation marks. [52]

5.4 Implementation

Implementation follows the system design phase in the waterfall model. For the STS operations' model, all parts presented in Fig.14 together with a container vessel were modelled. All FMS and STS models repeating in Fig. 14 are uniform copies of each other, although the architecture supports also the use of varying types. The following sub-chapters describe the implementation of each sub-model.

5.4.1 Operations simulation manager

Configuration parameters that define the simulation scenario are read in OSM. User defines the parameters in an XML document. The document is given to OSM, which converts the parameters into Simulink-compatible format. For this purpose, a separate MATLAB script was written. Configuration parameters determine the number of discrete berths and STS cranes per berth, the cranes' types and the berths' positions in terminal coordinates. In addition, wind conditions, vessel's fill rate and operation mode (loading/discharging) can be set.

The model supports up to eight discrete berths. The maximum number of STS cranes per berth is eight. Consequently, the maximum number of STS cranes supported is 64. The maximum number of supported machines is chosen based on the information of existing terminals. However, if a need for a larger system occurs in future, the model can be easily expanded.

Besides the configuration parameters, vessel models used in simulations are also defined in OSM. For this thesis, a single vessel was modelled. The implemented model is based on a geometry of a real vessel. The modelled vessel has a capacity of 4,300 TEUs. Its cargo area is approximately 240 m long and 40 m wide. Containers on deck can be piled in stacks 15 rows wide and eight tiers high. Hold has slots in 13 rows, and in the middle of the vessel the highest stacks reach the height of seven tiers.

The vessel geometry was captured from a real XML message sent between a TOS and an FMS. The message defines the structure of vessel's container area, including logical positions for all slots, acceptable container types, and the slots' exact coordinates in transversal and longitudinal direction. The XML message reports the coordinates against vessel origin. Vessel origin locates in the middle of the vessel in transverse direction and in the aft of container area in longitudinal direction. A function was implemented in the model that reads the XML file and picks all relevant information from it. The function generates a multi-dimensional array that includes information of each slot's logical position, exact coordinates and the type of container it can contain. Vertical direction coordinates that are not included in the XML message are created separately based on standardized container heights (see Table 1). All coordinates are converted into corresponding terminal coordinates. The generated matrix forms the vessel model. All information considering a specific slot is saved in an element that has the index corresponding to the slot's logical position.

5.4.2 Terminal operating system

TOS takes care of container and hatch cover generation along with job creation and sequencing. TOS generates the containers for simulations according to the configured vessel fill rate and rules presented in Chapter 3.2. Starting from hold, the vessel's empty slots are filled with containers until the given fill rate is reached. Hatch covers are generated based on the information from [30]. Three rows wide, 40 ft long, and 22 tonnes heavy hatch covers are placed on top of the hold area.

Job creation and sequencing is done based on the selected operation mode. The task of job sequencing corresponds to the task of solving QCSP. As stated in Chapter 3.3, QCSP means determining the optimal container handling order in a way that overall operation time is minimized. When solving QCSP, the number of crane movements and their distances, idle times and differences in workloads should be minimized and interferences between adjacent cranes avoided. In literature, QCSP is mostly solved with heuristic optimization models (see Chapter 4.2.1). The optimization algorithms differ in the way they allocate containers. Bay-based algorithms allocate complete bays to individual STS cranes and are considered the simplest to execute. The algorithms that allocate smaller units produce usually more balanced workload distributions between STS cranes but are often more complex and require longer computational times. [22, 31]

For the scope of this thesis, two different job sequencing algorithms for vessel discharging were implemented. As the focus lies on precise modelling of STS crane movement and vessel geometry instead of TOS algorithms, and the model requirements in Chapter 5.2 urge for fast computational times, the complex optimization models proposed in literature were not directly used. Instead, two different intuitive bay-based algorithms relaying on common sense were implemented. The implemented job sequencing algorithms adapt the basic principles of a QCSP algorithm presented in [22]. The algorithm proposed in the study determines the bay allocation as follows:

- Workload on each bay is calculated (the number of containers heading to quayside)

- Bays are partitioned into consecutive bay segments and assigned to separate STS cranes. The partition is done by minimizing the longest operation time of STS cranes. An average time estimate of the operation's duration is used in calculations
- The workloads of bay segments are compared and a suggestion to shift workloads between adjacent cranes is proposed in order to achieve more balanced workloads
- Bay segments are tuned accordingly and assigned to STS cranes for execution

The algorithms implemented in this thesis were made with the following principles:

- Workload on each bay is calculated (the number of containers heading to quayside)
- The bays are partitioned into consecutive bay segments and assigned to separate STS cranes. The partition is done in a way that each STS crane has approximately the same number of containers to operate

After allocating bays, the implemented algorithms calculate the discharging order of containers within the bay segments. This is where the algorithms differ: one of the algorithms calculates the order by allowing bidirectional inter-bay gantry movement, whereas the other allows only unidirectional inter-bay movement. Inter-bay gantry movement occurs when an STS crane moves from a 40 ft bay to another 40 ft bay. Intra-bay gantry movement is the movement that takes place when an STS crane moves within a 40 ft bay from a 40 ft position to one of the adjacent 20 ft positions or vice versa [22, 23].

The bidirectional algorithm produces a job sequence, where a single STS crane discharges all containers on a specific tier within its bay-segment before moving to a tier below. Consequently, all containers on the same tier are discharged as the crane moves from one edge of its bay-segment to the other edge. The job sequence produced by unidirectional algorithm follows a different principle: a single STS crane discharges all containers within a 40 ft bay before moving to the next 40 ft bay. This way the inter-bay movement of STS crane is always unidirectional.

Fig. 17 and Fig. 18 illustrate the two job sequences. In both figures, an STS crane has a bay segment that reaches from bay 01 to bay 15. In unidirectional discharging (Fig. 17), STS crane discharges first the containers from bay group 01-03 tier by tier. After it has discharged all required (blue) containers, it moves to the next bay group (05-07) and starts to discharge yellow containers. The procedure is repeated until the crane has discharged the final bay group (13-15) of its bay segment. In bidirectional discharging (Fig. 18), an STS crane moves from bay 01 to bay 15 while discharging all containers on the highest tier. After the containers are discharged, the crane moves to the tier below and starts to discharge containers while moving back from bay 15 to bay 01.

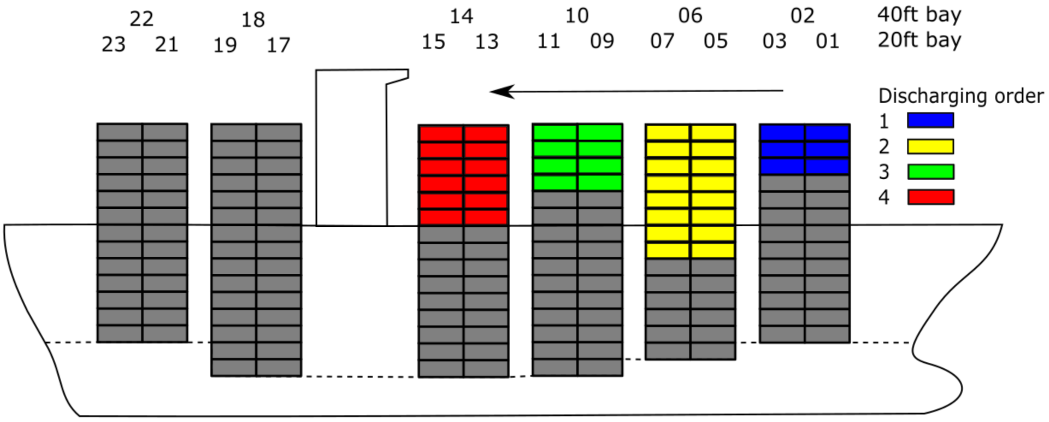


***Figure 17:** Unidirectional discharging*

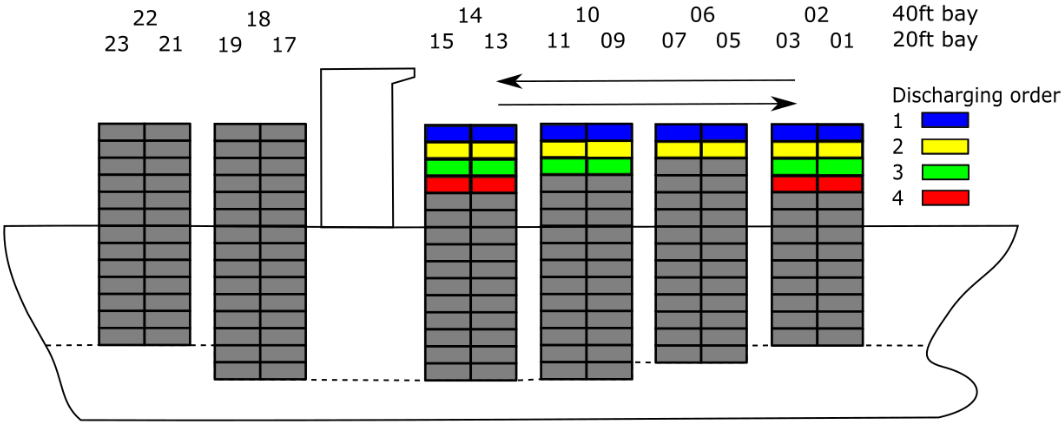


***Figure 18:** Bidirectional discharging*

The job sequences in both algorithms are generated in a way, that while working on a specific bay, the containers in rows closest to quay wall are discharged first. This way the containers are out of the way when operating containers in rows farther from quay wall. Fig. 19 illustrates the discharging order of rows.

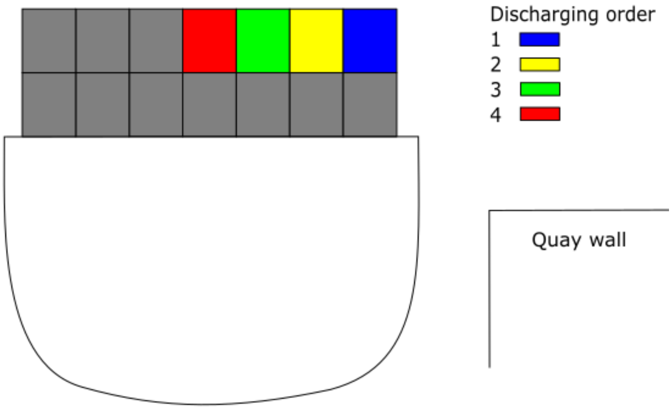


Figure 19: Discharging order of rows

5.4.3 Visualization

Visualization is performed with Unity. The fixed objects used in visualization, such as vessel body and quayside infrastructure are configured in a separate XML document. The document specifies the dimensions and coordinates of the objects. Unity can read the XML file and initialize the objects before simulation. Simulink and Unity communicate with each other via UDP protocol. A separate Simulink model connecting the visualization software and Simulink was provided and used in this work with small editions.

The interface model in Simulink sends all relevant information of the simulation to Unity. When TOS generates containers, the container information is sent concurrently to visualization for container initialization. During STS operations, the model sends information of STS cranes' positions and spreaders' statuses at every time step. Fig. 20 presents the visualization implemented in Unity, when two STS cranes are serving the modelled vessel.

Figure 20: *Visualization of two STS cranes serving the modelled vessel in Unity*

5.4.4 Fleet management systems

An STS crane moves according to routes it receives from FMS. FMS builds the routes based on jobs it receives from TOS. A job defines the logical target position for movement. FMS translates the target position into exact coordinates. The routing algorithm creates a route between current and the target position. When a new job arrives, first the adjacent cranes' positions are checked. If a collision is possible, crane must wait until the interfering crane has finished its job and moved aside. Secondly, the obstacles between trolley's and hoist's current and target position are checked. The routing is done accordingly: if obstacles occur between the straight line from point A to B, the route is sliced into pieces in a way that collisions are avoided. This means keeping the safety distance between obstacles and the spreader large enough in all cases. In STS operations, obstacles can always be passed from above. The generated angular routes are rounded to correspond operators' behaviour, for operators seldom drive the crane angularly. Fig. 21 presents a simple example of trolley and hoist routing. The dotted line presents the calculated route whereas the solid line is the executed rounded route.

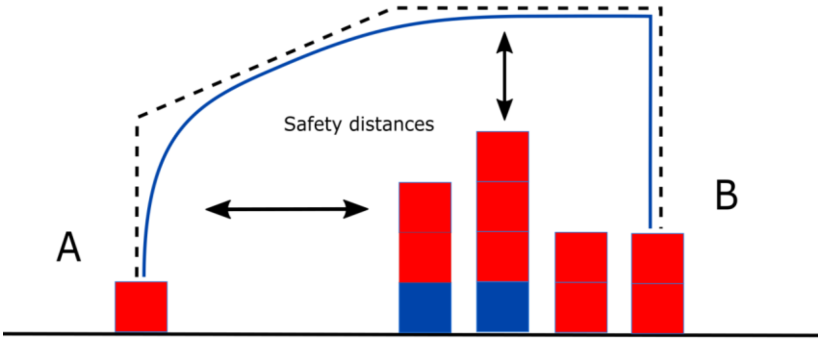


Figure 21: *Trolley and hoist route generation*

5.4.5 Ship-to-shore crane

A single-trolley STS crane equipped with a single-lift spreader was modelled. The crane works on a single cycling operation mode. The model supports three different STS crane types: Panamax, Post-Panamax and Super Post-Panamax (see Chapter 3.1). Based on the type selection, external dimensions along with kinematic and operational parameters are determined. Kinematic parameters include for example accelerations, decelerations and velocities of each movement axis. Operational parameters define for example the safety distances between adjacent cranes and the time delays that occur when picking or grounding a container.

An STS crane has three movement axes (see Fig. 6). A ready-made universal model imitating the movement of an object was provided by Kalmar and used in this implementation. The model captures object's motion's kinematics and generates a movement profile based on model inputs. User can define the motion's starting and ending position, its target speed and allowed acceleration and deceleration. The profile is outputted from the model, including position, speed and acceleration information. The profile generator model is a discrete model. A separate profile generator model was used for every movement axis of an STS crane, i.e. for gantry, trolley and hoist movement.

Picking and grounding of a container does not happen in a split second. In a picking job, operator drives the hoist above a container and secures the container to the spreader. Securing takes time, as the operator must make fine-tuning to the spreader's position before locking to the container. This attaching operation is modelled with a time delay. After the hoist reaches its target position, a time delay determined by user must pass before the picking job is finished. In a grounding job, operator drives the hoist again to target position and unlocks the container. The unlocking is modelled in the same way with a time delay. Operations' safety is considered in the model by restricting STS cranes' gantry movement. Gantry is not allowed to move before hoist is lifted above a specific safety height and trolley is driven to shore.

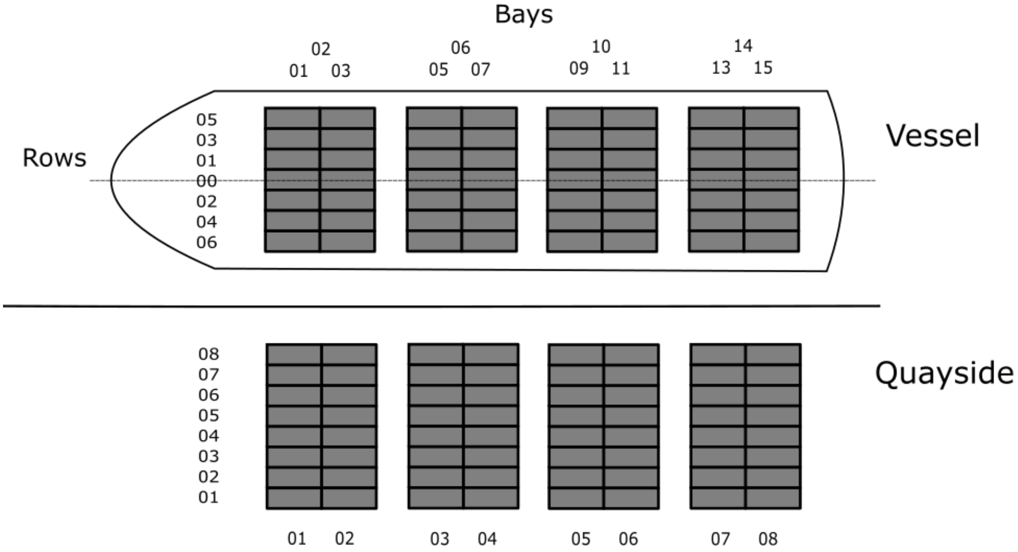


Figure 22: *Bay and row indexing of slots*

Quayside area was modelled similarly to container vessel. A multi-dimensional array was created that includes information of each slot's logical position and exact coordinates. The slot coordinates were generated based on dimensions of a 20 ft container. Diverging from the vessel model, quayside's bay indexing is not dependent on the container type. Consequently, the indexes increase systematically one by one. If a 40 ft container is grounded on a slot, it reserves also the next slot. Similarly, row indexing increases always by one when moving from backreach towards quay wall. Fig. 22 presents the bay and row indexing of both vessel and quayside.

6. VALIDATION AND RESULTS

After a simulation model is implemented, its similarity to the modelled system must be validated. The simulation model must be able to reproduce the real system's behaviour under different conditions with desired accuracy. Validation means comparing the simulation outputs of a specific scenario to the outputs measured from the real system under corresponding circumstances. [4]

In this chapter, the implemented STS operations model is validated and tested through simulations. The simulated outputs are compared to values found in literature. Test computer's technical specifications are described in Table 7.

***Table 7:** Test computer's technical specifications*

CPU	AMD Ryzen 5 2500U 2.0 GHz
Memory	8.0 Gb RAM
GPU	Radeon Vega Mobile Gfx
Operating system	Microsoft Windows 10 Home

As all discrete berths are independent and their models are uniform, only a single berth is simulated. The simulations focus on a scenario where the modelled vessel is discharged with Post-Panamax STS cranes. The simulation model considers lifting of hatch covers, non-crossing constraints between adjacent STS cranes, and various container weights and wind conditions. Preparations preceding the container operations, such as berthing and removal of lashings, are excluded. Delays caused by machine failures, drivers' skill level, changing of shifts and lunch breaks etc. are neglected. HT is not included in the simulations. Exclusion of the HT corresponds to a case where containers are grounded on wharf and no delays occur due to HT. This is realistic in terminals where HT is performed with ShCs, SCs or reachstackers, and their number is large enough to ensure STS operations without delays [50].

This chapter is divided as follows: In Chapter 6.1, customizable parameters of the model are tuned to correspond values from literature. In Chapter 6.2, the model is validated through work cycle analysis. Also, the effect of container weights and wind speeds on operations is studied. In Chapter 6.3, complete discharging of a full vessel with a single STS crane is simulated. Two different discharging strategies are used, and the simulated productivities are compared to literature values. A sensitivity analysis with different kinematic parameters is performed. In Chapter 6.4, the simulation of vessel discharging with varying number of STS cranes is studied. Interferences between adjacent cranes along with cranes' idle times are measured and compared to values presented in literature. Further, the simulated productivities are analysed.

6.1 Parametrization

In order to get comparable simulation data, parameters of the implemented model must be tuned to correspond real-life equivalents. The implemented vessel model has a capacity of 4,300 TEUs and lashing bridges on deck that reach up to two tiers high. The width of the container area is 40 meters at its maximum. A suitable crane type for serving the vessel is a Post-Panamax STS crane. As stated in Chapter 3.1, a Post-Panamax crane has approximately an outreach of 45 – 55 meters [3]. External dimensions of STS cranes in the model were set accordingly.

Table 4 presented typical STS crane specifications for a conventional STS crane. Kinematic parameters for the crane model were selected accordingly together with the information provided by Kalmar. Selected values are presented in Table 8. Hoisting speeds for full and empty containers were set to 1 m/s and 2 m/s, respectively. Trolley speed was set to 3 m/s and gantry speed to 1 m/s. The speed of spreader's telescopic motion was set to 0.22 m/s according to technical specification of a real spreader [45].

Table 8: *Kinematic parameters used in simulations*

Gantry speed	1	m/s
Trolley speed	3	m/s
Hoist speed – Full	1	m/s
Hoist speed – Empty	2	m/s
Spreader speed	0,22	m/s

Safety distance that must be maintained between adjacent cranes was determined from literature. Two cranes working next to each other must remain a safety distance of two 40 ft bays in between [40, 50]. Wind speed was set to fluctuate between 5 - 7 m/s, which corresponds to normal wind circumstances in coastal Finland [18]. Container weights were generated based on containers' loading capacities reported in Table 1 and stacking principles presented in Chapter 3.2. Grounding position for containers was set to backreach, close to the portal leg. Hatch covers' storing position for the time of hold operations (i.e. containers locating in hold are handled) was set to crane portal.

Time delays that express the fine tuning and locking of a spreader during grounding and picking were determined next. According to Bartošek and Marek [3], the time required to load a single container from wharf to vessel hold with a Post-Panamax crane follows the timeline presented in Fig. 23. The whole operation takes 52 seconds in total. The time delays for picking and grounding are 13 seconds both, whereas the time delay to find cell guides in hold is 10 seconds.

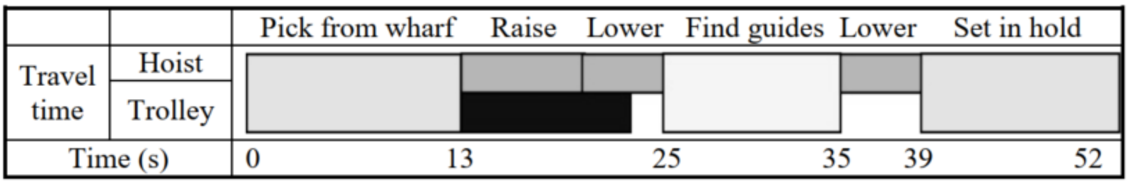


***Figure 23:** Time required for loading a container from wharf to vessel hold [3]*

To get a broader view of the matter, the delays in Fig. 23 were compared to video material of STS operations. Video material from port of Antwerp [16] suggests that the average value for picking a container from wharf is only 5 seconds. The time spent to find the cell guides is approximately 4 seconds, while grounding in hold takes 4 seconds. The operator in the video seems quite experienced, thus the values are probably close to optimum. In another video [46], discharging of containers from hold is filmed. The time to find guides is approximately 10 seconds, whereas the picking takes 6 seconds. Grounding on top of a HT vehicle takes 10 seconds. Although the videos don’t mention the types of STS cranes used, the values are relevant, for the tuning operations of a spreader are more dependent of the spreader’s features, vessel’s structure and operators’ skill level rather than the crane type.

It should be noted, that twist lock operations impact on time delays. When loading containers from ground onto a vessel deck, stevedores must insert twist locks to the containers by hand. Similarly, when discharging, the twist locks must be removed from containers coming from deck, provided that the containers are landed on ground instead of HT. Inserting and removing of twist locks takes approximately 8 seconds [10].

Time delays set to the model for discharging were based on average values from [3, 10, 16, 46] and are presented in Table 9. The values were tuned relatively large to avoid too optimistic estimates. Time delay for picking was set to 15 seconds and it includes the time spent for finding the guides. On tiers where the guides do not reach, the time delay reserved for guide finding is assumed to be spent on more challenging spreader tuning. Time delay for grounding containers from hold was set to 6 seconds and for grounding containers from deck to 15 seconds due to twist lock operations. For hatch covers, time delay for picking was set to 16 seconds and for grounding to 13 seconds. The values for hatch cover operations were determined from [17].

***Table 9:** Time delays used in simulations*

Action	Time delay (s)
Pick	15
Ground from hold	6
Ground from deck	15
Pick hatch cover	16
Ground hatch cover	13

6.2 Validation

After parametrization, STS operations model is validated. To measure the model's quality, a simple classification method presented in Table 10 was proposed. If the simulated values correspond to values reported in literature by over 95 %, the result is excellent. With over 90 %, the result is good, and with 85 % satisfactory.

***Table 10:** Quality classification for validation*

Quality	Correspondence
Excellent	> 95 %
Good	> 90 %
Satisfactory	> 85 %

The implemented model is validated through work cycle analysis. A work cycle of an STS crane was presented in Fig. 7. The work cycle consists of two different parts, a pick job and a ground job. In a pick job, operator drives a spreader above a container to be picked and secures to it. In a ground job, the operator drives the container to the grounding position and unlocks the spreader.

For work cycle validation, a scenario where a bay full of containers is discharged was simulated. The simulations excluded all gantry movements, i.e. inter-bay and intra-bay movements. According to the simulations, the average work cycle time for containers on deck was 109 seconds and 117 seconds for containers in hold. Consequently, the average work cycle time for container operations was 113 seconds. For hatch cover operations, the average cycle time was 102 seconds.

Simulations indicate that the operations in hold are slower than the operations on deck. Even though the time delay for grounding in hold operations was set 9 seconds smaller, the average work cycle time was still 8 seconds longer. The difference results from vessel geometry. Hoist must travel a longer distance to reach containers in hold. Fig. 24 illustrates the simulated average work cycle times when containers are discharged from different tier positions. The average work cycle times vary approximately by 10 seconds in deck operations and by 20 seconds in hold operations. In hold operations, moving one tier lower increases the work cycle time by 2.8 % on average. Smaller work cycle times occur on deck, where the traveling distances for hoist are shorter. The smallest work cycle times take place above lashing guides on the fourth tier, where traveling distances for hoist are the shortest. Picking a container from higher or lower tier on deck increases the average work cycle time by 1.8 % per tier. The increase is caused by the implemented routing algorithm. When spreader moves between the vessel and shore, hoist must always be lifted to at least at the height of the fourth tier in order to avoid collisions with lashing bridges and vessel structure.

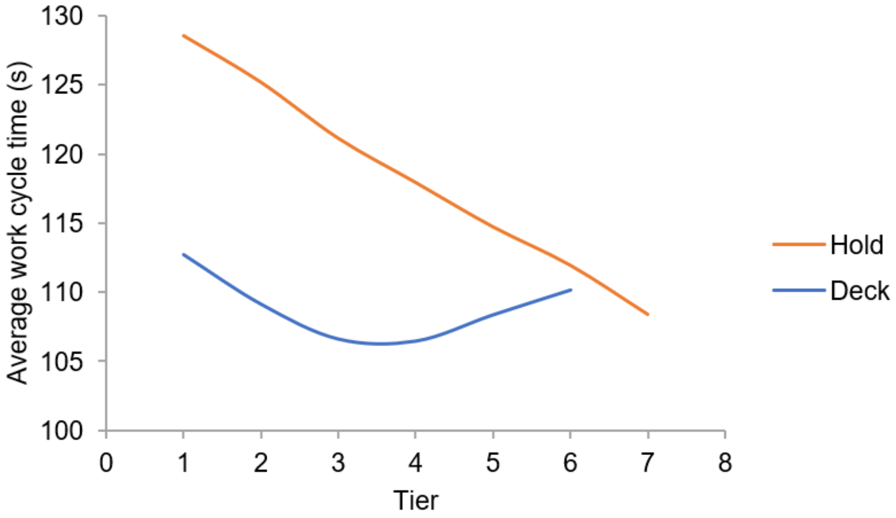


Figure 24: *Average work cycle times when containers are discharged from different tier positions*

Also, the distance that trolley must travel affects to work cycle times. In this regard, there are no differences between operations in hold or deck. When picking a container from one row farther from the quay wall, the average work cycle time increases by 1.9 %. Fig. 25 presents the average work cycle times in different rows. As can be seen, the work cycle times increase almost linearly along with the trolley's travel distance. Fig. 26 concludes the average work cycle times and illustrates how they change according to container's position. Lashing bridges are drawn in the figure and they reach up to two tiers high.

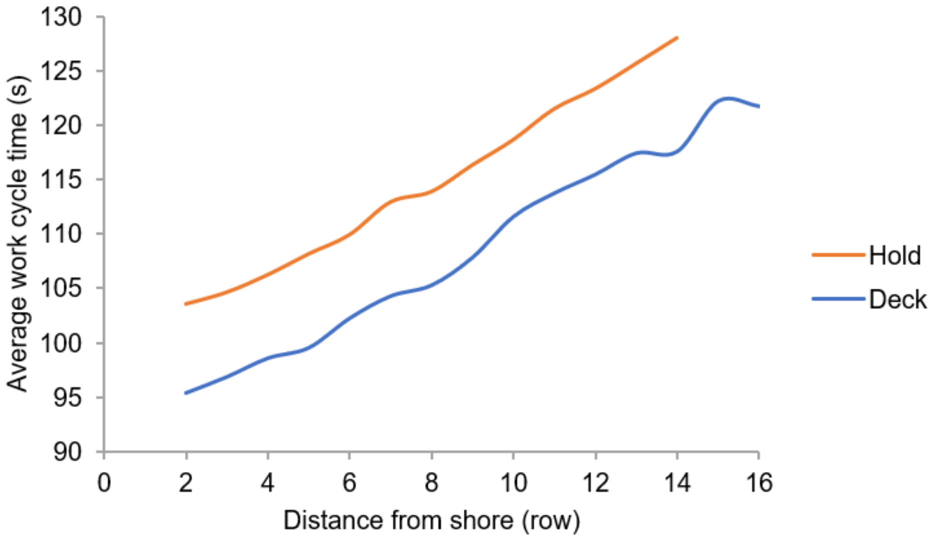


Figure 25: *Average work cycle times when containers are discharged from different row positions*

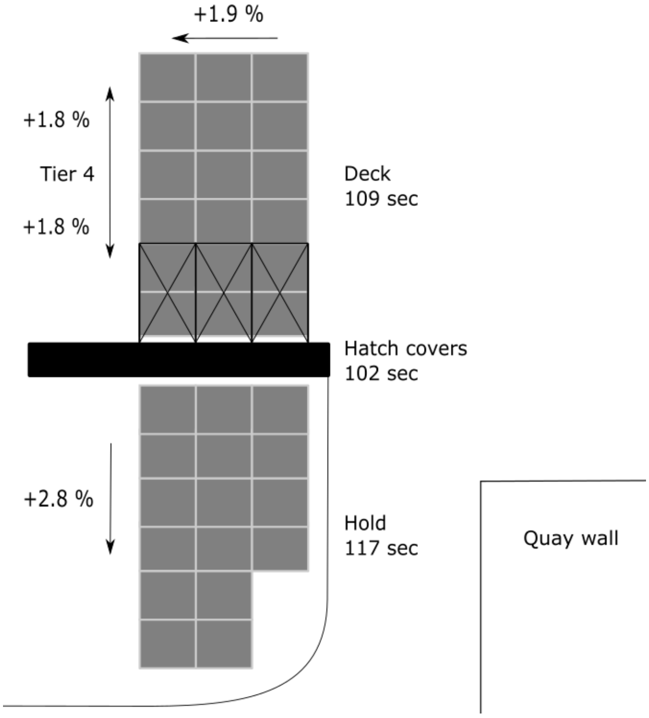


Figure 26: *Average work cycle times and vessel's geometry's impact on work cycle times*

The average work cycle times simulated are relatively close to value reported in literature. According to Goodchild and Daganzo [19], a single work cycle takes approximately 105 seconds. The value given in [19] is based on measurements from real operations. The value deviates from the simulated container operations work cycle time by 7.6 %. If hatch cover operations are included, the difference is only 4.1 %. The fact the simulated work cycle times are near the literature value is encouraging. Matching accurately to the reference value is not very realistic, as the test environment is not described in the study. After all, the work cycle times are dependent of the STS crane and HT equipment types used, vessel geometry, container weights, wind speed and grounding position of containers.

To study the effect of containers' grounding position on work cycle times, a scenario where containers were grounded in the middle of crane portal instead of backreach was simulated. The results indicate, that the work cycle times are reduced approximately by 5 % due to shorter trolley traveling distances. Consequently, if containers are grounded in portal, the average work cycle time for container operations reduces to 107 seconds, which differs only by 2 % of the value reported in [19].

It should be noted, that when long work cycle times occur, HT equipment has more time to transport containers to/from yard operations area. When handling containers with short work cycle times, faster transportation is needed. Therefore, it might be necessary to use a larger number of HT equipment to assure STS cranes can work without idle times. This is relevant especially in situations, where HT equipment without a picking capability (TTUs or AGVs) is used.

After work cycle simulations, gantry movement was examined. Lee *et al.* [53] suggested that an inter-bay gantry movement to adjacent 40-foot bay takes approximately 60 seconds. In the implemented model, the movement takes 40 seconds. It is relatively difficult to estimate the accuracy of the proposed values. The study made by Lee *et al.* [53] doesn't specify how the value is estimated or what type of STS crane it considers. The simulated values are based on gantry kinematics and consequently rely on physics. However, the simulations don't consider delays caused by human behaviour, such as visual observing of obstacles before movement or the imprecise positioning of gantry. On the other hand, Vis and Anholt [50] present that crossing to the next bay takes 20 seconds on average. The simulated value is the average of the two literature values, which is an acceptable result. Still, it should be kept in mind that gantry movement's influence on STS operations' productivity is relatively low, as only a few percent of the operational time is spent on it (see Chapter 6.3).

Next, the effects of container weights and wind speeds on operations were studied. Container weights affect directly to the hoist kinematics, as its acceleration and speed change according to load. To analyse container weights' effect on work cycle times, discharging of empty and full containers was simulated. A complete bay on deck was discharged with both weights, while wind was constant at 6 m/s. The minimum and maximum container weights were set according to Table 1. The simulation results indicate, that discharging full containers is 6 % slower in average than discharging empty containers.

While container weights effect on hoist movement, wind speed effects on trolley and gantry movement. Wind speed's influence was studied by simulating discharging operations with varying wind speed values. Work cycle times were 42 % faster in normal coastal circumstances (5-7 m/s), when compared to stormy conditions with wind speeds of 16 - 18 m/s. At wind speeds over 20 m/s, operations are usually halted to prevent damages for the equipment.

Simulations indicate the model can describe the behaviour of STS operations with good accuracy. Average work cycle times are close to values reported in literature, as shown in Table 11, and the environmental circumstances have a distinct effect on operations. Vessel geometry and containers' grounding position impact clearly on work cycle times. Hence the model provides a realistic environment to simulate scenarios where containers from a specific area are operated. Similarly, varying container weights and wind speed add realism to the simulations.

Table 11: *The correspondence between simulated average work cycle times and values reported in literature*

Grounding position	**Correspondence to literature**	**Quality**
Portal	98 %	Excellent
Backreach	92 %	Good
Backreach (including hatch covers)	96 %	Excellent

6.3 Discharging with a single ship-to-shore crane

After parametrization and validation of the STS operations model, complete discharging of a full container vessel was simulated. In the simulation scenario, 71 % of the vessel's containers were 40 ft long. As one 40 ft container corresponds to two TEUs, the total number of containers on the vessel was 2,514. The average productivity, vessel turnaround time, and the times spent for hatch cover operations and bay movements were measured.

First, the discharging was simulated with both implemented job sequencing strategies: unidirectional and bidirectional job sequencing. The average productivity with the former strategy was 30.4 mph, while it was 29.5 mph with the latter. The difference for the favour of unidirectional discharging strategy was caused by the lesser number of required inter-bay gantry movements. Gantry movements in bidirectional job sequencing took approximately 6.1 % of the total time while in unidirectional job sequencing the share was 3.0 %. Vessel turnaround times for unidirectional and bidirectional cases were 82.6 and 85.2 hours, respectively.

Literature provides few benchmark values to compare the simulated productivities. Most of the studies don't specify how the values are received in detail. Typically, the types of STS cranes, spreaders, vessels, or HT equipment are not described. In addition, containers' picking/grounding positions on shore are not informed. As seen in previous chapters, all these matters influence on productivity. Although the exact reference productivities are missing, results reported in literature indicate that the average productivity is typically around 29-30 mph, which is close to the simulated value [9 (p. 53, 171), 13, 14, 53].

Even though the turnaround time and productivity were worse in bidirectional discharging, the strategy still has its upsides. Bidirectional strategy maintains a better balance across the vessel during STS operations. As containers are discharged one tier at a time, weight distribution stays balanced during the operations. However, bidirectional discharging can be highly inefficient when discharging small vessels, where the number of required inter-bay movements is large compared to the number of containers per bay. Also, the strategy leaves STS cranes more vulnerable to interferences between adjacent cranes. As the cranes move back and forth in their bay segment, the probability that two adjacent cranes need to operate on bays close to each other increases along with the probability of interferences. Due to the downsides of bidirectional job sequencing, unidirectional strategy is used in further simulations.

Next, a sensitivity analysis of the effects of STS crane's kinematic parameters to productivity was performed. Discharging of a full container vessel was simulated with low and high operational speeds based on Table 4. Table 12 presents the simulation results and the kinematic parameters used. With low operational speeds, the productivity was only 17 mph, while the vessel turnaround time was 146 hours. With high operational speeds, the productivity was 34 mph, and the turnaround time 73 hours. The simulations indicate that the kinematic parameters impact greatly on STS operations' productivity. The vessel turnaround time with low operational speeds was exactly twice as long as the turnaround time with high operational speeds.

***Table 12:** Simulation results gained with low and high operational speeds*

	Low	**High**	
Gantry speed	0,8	1,2	m/s
Trolley speed	1,2	4,2	m/s
Hoist speed - Full	0,4	1,5	m/s
Hoist speed - Empty	0,8	3	m/s
Productivity	17	34	mph
Vessel turnaround time	146	73	h

It should be kept in mind, that the simulations don't consider changing of shifts, lunch breaks or operators' skill levels. The simulations neglect also HT, and consequently represent pure STS crane operations. Therefore, the simulated productivities are close to the scenarios' maximum. As the productivities are strongly dependent on cargo profile and environmental circumstances, the simulation results are case-specific and cannot be generalized.

6.4 Discharging with multiple ship-to-shore cranes

To study the impact of STS cranes' quantity on operations' efficiency, complete discharging of a vessel was simulated with multiple STS cranes. Even though the model supports up to eight STS cranes, the maximum number of cranes used in simulations was six. The vessel's cargo area doesn't have room for more cranes to operate. Table 13 presents the simulation results.

***Table 13:** Simulation results of vessel discharging with varying number of STS cranes*

Number of STS cranes	**1**	**2**	**3**	**4**	**5**	**6**
Average productivity (mph)	30.4	30.4	30.4	29.9	28.8	26.0
Vessel turnaround time (h)	83	46	32	25	23	22
Average idle time (%)	0	0	0	1.2	4.6	15.4
Interference exponent α (-)	1	1	1	0.99	0.97	0.90
Largest difference in STS cranes' working time (h)	0	9	9	7	14	19

As shown in Table 13, the average productivity of STS operations per crane is 30.4 mph, when the number of STS cranes is one, two or three. However, if four or more cranes are used, the productivity starts to decrease. This is caused by increased idle times: some of the cranes must stand idle and wait for their adjacent crane to move out of the way in order to avoid interferences. With four STS cranes, the average idle time is 1.2 % of the cranes' total operation time. When serving the vessel with five cranes, the percentage rises to 4.6 % and with six cranes to 15.4 %. The increased idle time reduces the operations' efficiency. This can be seen clearly in the case of five STS cranes, for the turnaround time is only two hours smaller when compared to operations with four STS cranes.

According to Schonfeld and Sharafeldien [39], the productivity loss caused by interference can be described by an interference exponent α $(0 < \alpha \leq 1)$. If q STS cranes are assigned to a vessel for an hour, q^{α} describes the real amount of productive STS crane hours. If α is low, interference between adjacent cranes is high and the productivity is low. Vice versa, large values of the interference exponent lead to high productivity. The value of α depends on the number of containers handled and the types of the vessels served [14]. According to empirical investigations performed in a Taiwanese terminal [14], the interference exponent varies typically between 0.8 and 1.0. The mean value for interference exponent in the experiments was 0.93. As can be seen from Table 13, the simulated interference exponent values are within the reference range. If all scenarios with more than one STS crane are considered, the average value for α is 0.97. However, if only the scenarios where interferes occur are considered, the exponent gets an average value of 0.95. It is apparent, that the size of the vessel affects strongly on interference exponents. If the served vessel is small, interferences occur with smaller number of STS cranes and therefore the average interference exponent is low. On the other hand, if the served vessel is large, interferences occur only with high number of STS cranes and hence the average interference exponent is also high.

Table 13 presents also the largest differences in STS cranes' working times. This means basically the time passed from the moment when the fastest STS crane has finished its work until the moment when the whole vessel is discharged, i.e. the slowest STS crane has finished its work. The number represents the balance between cranes' workloads. With two to three STS cranes, the difference is caused only by the job sequencing algorithm. The algorithm doesn't divide the jobs optimally, hence some cranes have larger workloads. As the algorithm applies bay-based allocation, and the differences in container quantities between bays are considerable, unbalanced workloads occur. However, when four to six STS cranes are used, the difference is affected also by idle times. Idle times cumulate with the unbalanced workloads and cause larger differences between working times. For example, if a specific STS crane is initially assigned with a workload well above average, and in addition its idle time is large compared to other cranes, the working time can grow excessive and the differences become large.

Fig. 27 gives an example how unbalanced workloads generate in bay-based allocation. In the example, a vessel is operated with three STS cranes. Each crane is assigned with an individual bay segment. The bay segments consist of bay groups. The number of containers in each bay group is marked with white number. The bay allocation produced by implemented algorithm is presented in the figure: bays 01-11 are assigned to crane one, bays 13-19 to crane two and the rest for crane three. Total number of containers in the first bay segment is 220 containers, 210 containers in the second, and 180 containers in the third. Consequently, large differences in workloads occur. The third crane finishes most likely first due to the smallest workload (180 containers). The first crane has the largest workload (220 containers) and hence it finishes the last.

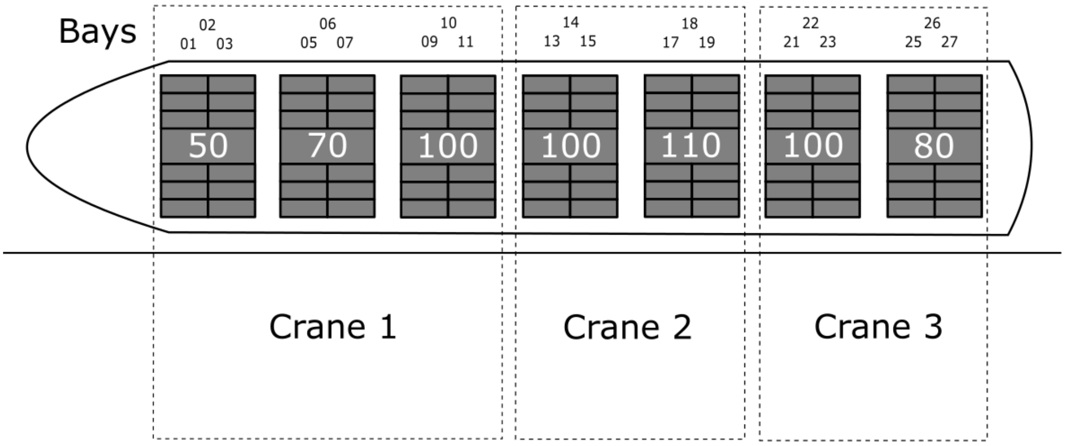
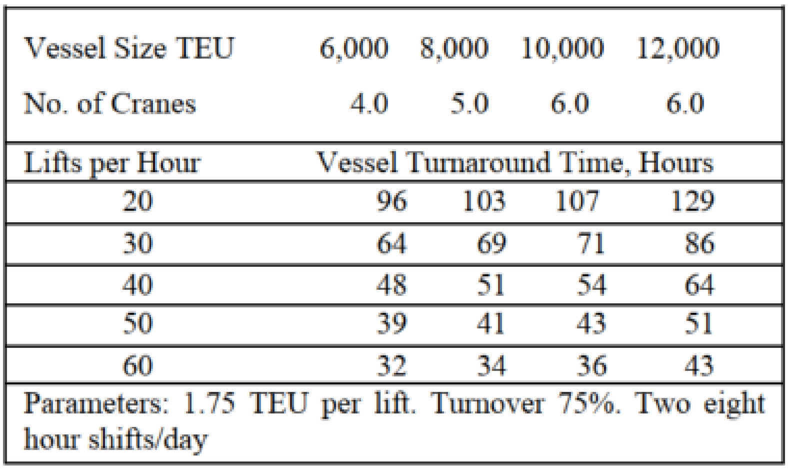


Figure 27: *Bay allocation*

Based on the matters described above, the optimal number of STS cranes for serving the modelled vessel is four. With four cranes, the vessel turnaround time is relatively low, while the interferences don't impact excessively on operations' productivity. The use of four cranes is also supported by Vis and Anholt [50], who suggest that a vessel with a workload of approximately 2,000 moves is typically served with four STS cranes. According to simulation results, increasing the number of STS cranes to five decreases the turnaround time only by 2 hours and lowers the productivity by 3.8 %. The reduction of productivity is not especially significant, but the differences in STS cranes' working times are considerable: finishing 14 hours before the slowest crane is extremely inefficient, especially if the finished crane is stuck in the middle of two unfinished cranes. The problem would emphasize even more in the case of continuous quay wall, for the finished crane could be assigned to work on another vessel.

Table 14 presents typical turnaround times for varying vessel sizes, when 75 % of the vessels' containers are exchanged. As three quarters of the containers are handled, the 6,000 TEU vessel in Table 14 corresponds roughly to a 4,500 TEU vessel with 100 % of containers exchanged. The share of 40 ft containers in vessels presented in Table 14 is 75 %, while it is 71 % in the modelled vessel. As the number of required moves in the reference vessel (2,570) is almost the same as in the modelled vessel (2,514), the reference vessel's turnaround times can be compared. If we assume, that discharging and loading operations take the same amount of time and the productivity is 30 mph, the vessel turnaround time for 6,000 TEU vessel is 32 hours with four STS cranes. However, as the values in Table 14 consider work shifts (two eight-hour shifts per day), 33 % of the reported turnaround times are unproductive. Consequently, the turnaround time corresponds to 21 hours, if cranes were operated night and day. The simulated turnaround time in our case was 25 hours, which is four hours more. However, in our case, the workloads between cranes were not optimized and thus a seven-hour difference in working times occurs. If the workload could be balanced better, and the time difference could be cut to half, the turnaround would be close to the value presented in Table 14.

Table 14: *Typical turnaround times for varying vessel sizes [55]*



Vessel Size TEU	6,000	8,000	10,000	12,000
No. of Cranes	4.0	5.0	6.0	6.0
Lifts per Hour	Vessel Turnaround Time, Hours			
20	96	103	107	129
30	64	69	71	86
40	48	51	54	64
50	39	41	43	51
60	32	34	36	43
Parameters: 1.75 TEU per lift. Turnover 75%. Two eight hour shifts/day				

Simulations indicate that the implemented model can represent the behaviour of STS operations when multiple cranes are used. The model produces credible estimates of operations' efficiency and considers productivity losses caused by crane interferences. On the other hand, the need for a more sophisticated job sequencing algorithm is apparent, for differences in cranes' workloads are considerable. With the test computer described in Table 7, simulations run approximately three times faster than real-time. If visualization is not used, the simulations run seven times faster than real-time. This can be considered as a good result, although there is still room for improvement as regards to the data structures and the amount of data used.

7. CONCLUSIONS

In this thesis, a simulation model of STS operations for productivity analysis was implemented with MATLAB Simulink. A visualization for the model was set up with Unity. The model describes the loading and discharging operations of container vessels with STS cranes. Multiple cranes can be assigned to work on a single vessel and up to eight discrete berths can be simulated simultaneously. Operations' productivity is evaluated by measuring the turnaround time of vessels, the number of containers moved per hour by an STS crane, and the cranes' idle time caused by interferences. A sensitivity analysis was performed to study how STS cranes' quantity and kinematic parameters impact on operations' productivity.

Before modelling, a requirements analysis was performed to state the specifications for the model (see Table 6). The requirements are mainly dictated by the terminal-scale simulation model where the implemented STS operations model is to be integrated. Models proposed in literature don't fulfil the requirements mostly because they are inaccessible to reader, lack the amount of detail, don't consider crane kinematics, and are implemented with different software.

The implemented model's architecture and features follow closely the main characteristics of the terminal-scale model. STS cranes are modelled in terms of movement kinematics that vary according to container loads and prevailing wind circumstances. The modelled STS cranes operate on a single cycling mode and are equipped with single-lift spreaders. Non-crossing constraints between cranes are considered, and HT is neglected. The model includes control logics that create realistic movement paths for cranes, determine containers' handling order and share the workloads evenly between cranes. The control system imitates algorithms used in real TOSs. In addition, a single container vessel was modelled, based on a geometry from a real vessel with a capacity of 4,300 TEUs. The vessel model includes hatch covers. In general, the model is designed to be highly configurable in terms of machinery and area layouts. The number of discrete berths and STS cranes is fully configurable in addition with berths' coordinates and STS cranes' operational and kinematic parameters.

The implementation was validated through simulations. For validation, operations on a single berth were examined. Customizable simulation parameters (operational and kinematic) were tuned to correspond literature values. Discharging of containers with a single STS crane was simulated and crane work cycle times were compared to values found in literature. The simulations indicate, that the average work cycle times match to the reference values with an accuracy of over 90 % (see Table 11). According to simulations, work cycle times are strongly dependent on STS crane types used, vessel geometry, container weights, wind speed and grounding position of containers.

After validations, the effects of STS cranes' quantity and kinematic parameters on productivity were studied. Discharging of a full container vessel was simulated with varying number of STS cranes. Even though benchmark values corresponding exactly to the simulated scenario in terms of STS crane and vessel types were not available, similarities between simulation results and literature could be found. Serving a vessel with low number of STS cranes leads to high productivity but results in long vessel turnaround time. A high number of cranes shortens the turnaround time but at the same time lowers the productivity due to increased interferences. The benefits gained in shorter vessel turnaround time with a larger crane capacity decrease as the interferences grow. The simulated average productivity of STS cranes was close to 30 moves per hour without interferences, which corresponds to typical values reported in literature. When the vessel was served with six STS cranes, the productivity was only 26 moves per hour due to large number of interferences. Simulations also indicated, that STS cranes' kinematic parameters impact greatly on operations' efficiency. When operations with a single STS crane were simulated using low and high operational speeds typical for a conventional STS crane, differences in productivity were significant. With low operational speeds the productivity was only 17 moves per hour, while it was 34 moves per hour with high operational speeds.

The simulations revealed also a flaw in the model: the implemented control system algorithm for workload sharing between STS cranes is not optimal. Workloads between cranes were not evenly balanced and some cranes had to work considerably longer than others. The problem in the control system is caused by the fact that the implemented control logic algorithm allocates the containers to cranes in large units and relies on common sense instead of sophisticated optimization methods. This was a conscious choice made in the planning phase: the focus in the modelling was concentrated on modelling of STS cranes' motions instead of TOS algorithms.

All in all, simulations indicate the model can reproduce the behaviour of STS operations well. All requirements set for the model are fulfilled, as the model is highly and easily parametrizable, includes a visualization, models crane movements accurately, follows the architecture of the terminal-scale model, and is capable to run multiple times faster than real-time. However, when utilizing the simulation results it should be kept in mind that the simulations don’t consider machine failures, lunch breaks, change of shifts, operators’ skill levels or possible delays caused by HT. Therefore, the simulated productivities represent the absolute maximum. This is the case especially if the TOS algorithm is improved in future, so that all inefficiency in the system is caused by the above-mentioned factors.

7.1 Future research

In order to extend the model’s usability in future, a few features and enhancements should be added to the model. First, the TOS algorithm should be improved to generate more balanced workloads for STS cranes. A better algorithm is achievable by using advanced optimization models proposed in literature or by changing the current algorithm to allocate smaller units. Second, a support for multi-lift spreaders should be added, as nowadays many STS cranes use them. Twin-lift spreaders are common, and the use of tandem-lift spreaders is growing constantly. With multi-lift spreaders a significant rise in productivity can be achieved, as multiple containers can be operated during a single cycle. Another target for development is to add a double cycling mode to the model. However, this requires more complex TOS algorithm as the operation order of containers must be carefully planned.

Currently the simulation model divides quay wall to discrete berths. An extension to the model allowing the simulation of continuous quay wall would extend the model’s versatility. With the support for continuous quay wall, it would be possible to simulate scenarios where STS cranes are moved from a vessel to another. In order to simulate long-term productivity of STS operations and to study the utilization rate of quay wall, a realistic vessel arrival pattern needs to be implemented together with logics to solve BAP. The arrival pattern should be customizable to correspond different types and sizes of container terminals. Also, the number of container vessel models should be increased.

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