Opportunities for peak shaving electricity consumption at container terminals

Applying new rules of operation to achieve a more balanced electricity consumption

ROBERT HEIJ

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GREEN EFFORTS

The GREEN EFFORTS, "Green and Effective Operations at Terminals and in Ports", is a collaborative research project, co-funded by the European Commissions under the Seventh Framework Programme, aiming at the reduction of energy consumption and improving a clear energy mix in the seaports and at terminals.

Partners:

- Jacobs University Bremen, Germany
- Fraunhofer Center for Maritime Logistics and Services, Germany
- Port of Trelleborg, Sweden
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- Hamburg Port Training Institute GmbH, Germany
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Picture front page: APM Terminals Gothenburg (Mercator media, 2014)

Maersk containership at APM container terminal
Photo: APM Terminals (2014)

Preface

Thank you for taking time to read this report. This research is the physical evidence of my work during the Master Thesis Project, completing the SEPAM Master program at the Delft University of Technology. This research gives an introduction into the development of the containerised transport and shows how to cope with the dynamics of the energy consumption of electrical terminal equipment (in particular the ship-to shore quay cranes). Because of the high energy peaks, caused by the simultaneous use of electrical terminal equipment, an energy consumption model is developed and presented. Is it possible to find new rules of operations which contribute to a more smoothened energy consumption and less energy related costs? You will find the answer in this report.

Next to writing this report, this last year has been a very rough one for me and my loved ones. So much has happened, resulting in true life-changing moments. We make our own plans, but we do not control the path that is before us. For that reason I would like to thank my wife Laura in particular: thank you for your support and everlasting love and dedication! I could not have done this without you next to me!

I would like to thank my graduation committee, existing of Lóránt Tavasszy, Ron van Duin, Michel Oey, Harry Geerlings and Patrick Vloemans. Many thanks for participating in my graduation committee and for all the meetings and the continuous feedback you provided! It was very helpful to me using your distinguished specialisms. This really helped me to keep a broad perspective on the dilemmas that are covered in this research. I also appreciate your flexibility and sympathy during the difficult period of my thesis process. Next I would like to thank the people of GREEN EFFORTS for the internship they offered me and for the many fruitful discussions I have had during the GREEN EFFORTS conferences. Also thanks to Tiuri van Rossum (Erasmus University Rotterdam), my partner in the GREEN EFFORTS project.

Last – but definitely not least! – I would like to thank my parents for their ongoing support during my Bachelors and Masters! There have been periods that I invested more time in extracurricular activities than in my study curriculum, which must have driven you crazy sometimes. But finally, your patience is rewarded! Also many thanks to my fellow students who have made my time at the TPM faculty extra lively. I really enjoyed working on this thesis, with this report as a final result!

Robert Heij
Delft, February 2015

Stacking cranes at the port of Hong Kong.
Photo: Jonathan Brennan (Flickr, 1 October 2013)

Summary

The throughput of containers is growing yearly (World Shipping Council, 2011). At the same time the capacity of containerships has grown from several hundreds of containers in the 1960s towards today's 19,000 TEU[1] carriers. In order to achieve efficient operations of these large containerships, container carriers require high handling speeds and low handling costs when visiting container terminals. This development stimulated continuous innovations at container terminals, resulting in growing automatisation of terminal operations.

Where minimisation of costs has always been a key performance indicator for terminals, over the last decade the environmental performance has become another important performance indicator. This environmental performance is enforced by governments and port organisations as well as carriers who demand less emissions for handling their containers at a container terminal to improve the green image of their company and products.

In order to save costs and to reduce the greenhouse gas emission (especially CO_2) at container terminals, more terminal equipment gets powered by more environment-friendly energy sources like biodiesel, hybrid systems or electricity. Nowadays most modern container terminals are even fully electric. With a focus on higher handling speeds, the peak capacity of terminal equipment (i.e. number of terminal equipment that are operating at the same moment) increases. Because of the high price that is paid for the highest observed peak demand (leading up to 20-30% of the terminals' energy bill), it is beneficial to keep the peak demand as low as possible to reduce the handling costs.

To investigate the opportunities for container terminals to reduce their peak demand, an energy consumption model is developed to visualise the energy consumption of terminal equipment at container terminals. The energy consumption model visualises the energy demand (kW/s) by focussing on the different movements that are executed by terminal equipment. This focus is important, since the energy consumption differs per movement. Hoisting a container consumes up to ten times more energy than a horizontal gantry movement.

Based on the energy consumption model a simulation model is developed to test rules of operation (i.e. changes to the business operational procedures) that reduce the peak demand of terminals. Two rules of operation are tested to analyse their effect on peak demand and handling time:

1) limiting the number of simultaneously lifting quay cranes;
2) limiting the maximum energy demand per second.

The potential reduction in peak demand is around 50% against an extra handling time of less than half a minute per hour. This can be achieved by reducing the maximum energy demand by 50%. By reducing the number of simultaneously lifting quay cranes the peak demand decreases up to 40%, which is lower than for limiting the energy demand per second. In this case the impact on terminal operations is also bigger, which makes it a less optimal solution.

When reducing the peak demand by 50%, a container terminal with eight quay cranes is able to reduce their peak related energy costs with about €249,000 per year; a major potential saving for container terminals, which shows the opportunity for peak shaving the electricity demand at container terminals.

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[1] Twenty-foot equivalent unit (TEU) is a standardised unit which is used worldwide to measure the capacity of container transport modalities (mostly ships) and throughput of containers (mostly at ports and terminals).

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Abbreviations

AGV	Automated Guided Vehicles
ASC	Automated Stacking Cranes
FEU	Forty-foot equivalent unit, a sometimes used unit for presenting the capacity of ships and container terminals in containers of 40 ft.
HDV	Heavy Duty Vehicle
IDEF	Integrated DEFinition
MSCTV	MSC Terminal Valencia
NCTV	Noatum Container Terminal Valencia
RMGC	Rail-mounted Gantry Cranes (also referred to as ASC)
RTGC	Rubber-tired Gantry Cranes
TEU	Twenty-foot equivalent unit, a standard size for presenting the capacity of ships and container terminals in containers of 20 ft. (40ft. container is 2 TEU)
TOS	Terminal Operation System

Containerships VIII at Nieuwe Waterweg in Rotterdam.
Photo: Nik Morris (Flickr, 4 July 2013)

1. Introduction

It is generally assumed that the container as we know nowadays was introduced in 1956[2] (Van Ham & Rijsenbrij, 2012). Since the introduction of the container its use and utility in transporting goods has grown. The share of containerised transport in seaborne trade increased from 2.75% (1980) to 16.5% (2013), while the total seaborne trade increased with 158% over this period (UNCTAD, 2013). The standardised size of the container (in 20ft. and 40ft. equivalents) makes it a suitable mean for transporting all kinds of products, ranging from multimedia and building material to clothing and shoes. Even temperature-sensitive goods like flowers, fruits and vegetables can be transported easily by temperature-controlled containers (known as reefers).

Although the general principle behind the transport of containers has not changed since its introduction, the scope (i.e. transport capacity and worldwide throughput) of the sector did change. The growing pressure from ship owners to handle ships as fast as possible increased the need for container terminals to improve their productivity. This need was satisfied by the ongoing automatisation of terminal processes. This development changed the way containers are handled at container terminals tremendously. Where the first container terminals half a century ago were small and simple, the newest container terminals have a very comprehensive and highly automated character.

Besides the need to increase the operational productivity, today's discussion about costs savings make container terminals more aware of the need to reduce the handling costs per container (including costs for terminal lay-out and terminal equipment). Besides, many freight distributors demand lower emissions to decrease the carbon footprint of their supply chain. This means that next to increasing productivity and decreasing the handling costs, container terminals should also focus on reducing the energy consumption (Port of Rotterdam, 2014).

However, there is tension between increasing the operational productivity and reducing the total costs. A higher productivity (expressed in TEU/hr) is mainly achieved by increasing the number of terminal equipment that is operating simultaneously. In case of electrical powered terminal equipment this might lead to a higher demand of electricity at a particular moment in time (i.e. peak productivity). Because terminals pay high tariffs for the highest peak (in kW) that is achieved during a year (see also paragraph 1.3), an increase in productivity (leading to higher peaks and subsequently higher handling costs) is contradictory to reducing handling costs (see Figure 1). The peaks in energy demand should therefore be prevented as much as possible to avoid these charges. This could however limit the simultaneous operational activity, leading to higher handling time of containerships, leading to more unsatisfied customers.

The challenge is therefore to find an optimum between increasing the productivity and decreasing the handling costs. This can be done by developing rules of operation that smoothen peaks in electricity demand at container terminals (in order to reduce the energy related costs), while monitoring the consequences for the handling time of containerships. This challenge is addressed in this research.

This first chapter outlines the context in which the containerised transport takes place and presents the objective of this research. In paragraph 1.1 the development of the containerised transport is described. Paragraph 1.2 presents the (inter)national environmental policies (e.g. regarding reduction of greenhouse gases and modal split) and the effect of these policies for container terminals. Because the continuous innovations at container terminals leads to more and more electrical terminal equipment, paragraph 1.3 looks at the pricing of electricity.

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[2] See paragraph 1.1 for a more detailed introduction of the container and the development of containerised transport.

Paragraph 1.4 presents the research design (including problem statement and research objective). Based on the research design the research methodology is presented in paragraph 1.5 and includes the research flow diagram, visualising the research approach that is used to answer the research questions. The chapter is finally concluded in paragraph 1.6.

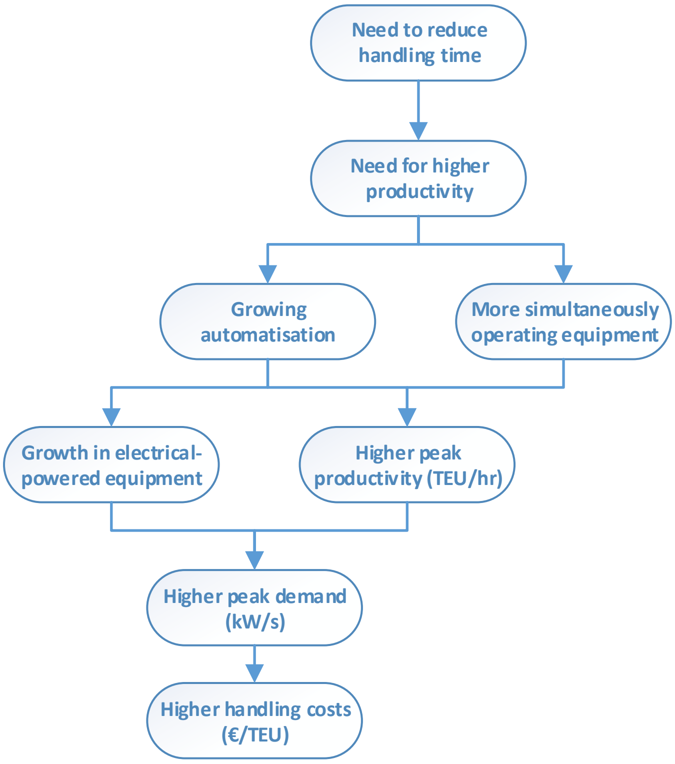

Figure 1: Visualisation of relation between reducing the handling time and higher handling costs.

1.1 Development of containerised transport

The idea of transporting goods in uniformly-sized containers was developed early 1940s by Leathem D. Smith, a shipyard owner, to make the handling of goods more efficient. During the Second World War the US army combined the transport of items of uniform sizes, leading to the development of a 8ft. container in 1947 (Van Ham & Rijsenbrij, 2012). However, the concept of the container as we know nowadays (the 20ft. and 40ft. equivalents) is introduced by Malcolm McLean in 1956. In that year the trucking company of Malcom McLean partially converted a tanker (the 'SS Ideal X'), enabling the ship to carry 58 bodies of trailer trucks on the platform (Cudahy, 2006). In the decades after this first transport of containers, the capacity of the worldwide fleet has increased enormously: from 58 TEU in 1956 to 6.4 million TEU in 1990 and almost 32.9 million in 2012 (Drewry, 2013). The annual worldwide transport of containers increased from 28.7 million TEU in 1990 to 153 million TEU in 2010 (World Shipping Council, 2011).

An important characteristic of the container is its standardised size. Although there is some variation in container sizes (Transport Information Service, 2014), the two most commonly used containers for sea transport are the 20 ft. container (equal to 1 TEU) and 40 ft. container (2 TEU or 1 FEU[3]). This standardisation of sizes allows an efficient transport with high-capacity container vessels. Since the first containerised transport in 1956, the size of the largest operating containership has increased continuously (see Figure 2). In 2013 the share of vessels with a capacity of more than 10,000 TEU is one seventh of the total fleet capacity (Lloyd's List Intelligence, 2013).

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[3] Forty-foot equivalent unit (FEU), used to express the capacity or productivity in 40ft. container equivalents. However, it is more common to express capacity or productivity in TEU.

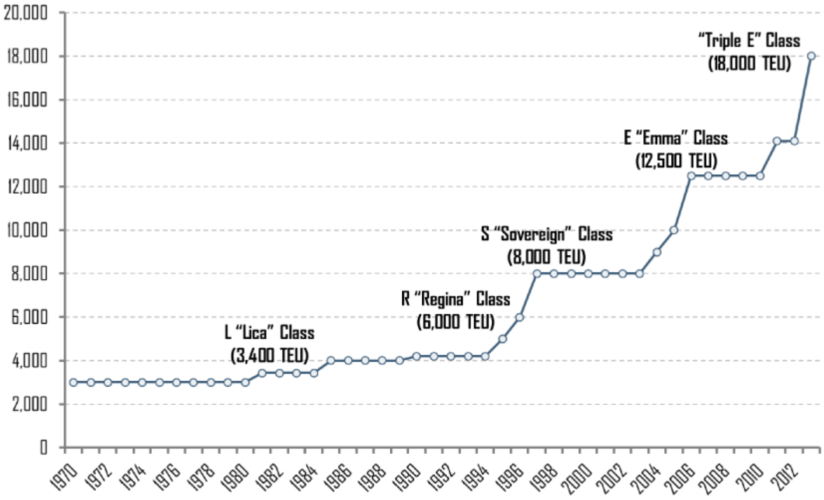

Figure 2: Growth of largest containerships available (by mid-2014).
Source: Rodrigue (Hofstra University, 2012).

It is foreseen that the growth in container ship sizes will not come to an end soon. In 2014, Maersk introduced the Triple-E ships, with a capacity of 18,000 TEU the largest operating containerships at that time (Maersk, 2013). By the end of 2014 the Triple-E series were surpassed by the CSCL Globe and CSCL Pacific Ocean, with a capacity of 19,100 TEU (Lloyds List, 2014). January 2015 the MSC Oscar was christened, with a capacity of 19,226 TEU (MSC, 2014). In the future the maximum capacity is expected to increase even more: STX Shipbuilding developed a 22,000 TEU containership (STX Shipbuilding, 2008) and the G6, a collaboration of six major container carriers, is planning for 23,000 TEU containerships (Shippingwatch, 2014). David Tozer, Container Segment Manager at Lloyd's Register is even expecting ships with a capacity of 24,000 TEU (ShippingWatch, 2014).

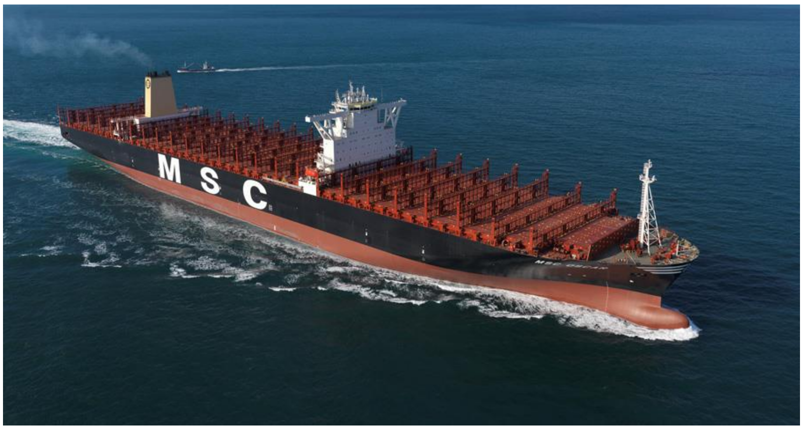

Figure 3: MSC Oscar (capacity: 19,226 TEU), shortly after its christening
(source: Daewoo Shipbuilding)

1.1.1 Handling of containers

A major advantage of the standardisation of containerised transport is the opportunity to facilitate intermodal transport. Barges, trains and trucks enable the inland transport of containers between sea port container terminals and its hinterland. Container terminals are therefore not only responsible for handling large containerships, but also for transhipping containers from and to barges, trucks and trains.

A common layout for modern container terminals can be seen in Figure 4. On the water side of the terminal (upper side of Figure 4) ship-to-shore quay cranes are responsible for handling containers between ship and terminal. The stacks, where containers are stored while waiting for further transhipment, are located behind the quay cranes. The stacking of containers is one of the most challenging processes for terminal operators because most containers have different origin-destination routes and are in need of different types of transhipment (i.e. from truck/train to ship, ship to truck/train or ship to ship). Next to that, the storage period at the terminal also differs for each container. The challenge is to have each container positioned on top of a stack when needed for transport in order to prevent unproductive moves. On the land side of the terminal (downside of Figure 4) the containers are transported between the stacking area and arriving/departing trucks and trains. A detailed explanation of the terminal processes is presented in chapter 2.

Most of the handled containers at container terminals are the standard dry containers, which are responsible for 89% of the containerised transport (World Shipping Council, 2013). The other 11% consists of reefers (used for transport of temperature-controlled goods) and tank containers (used for transport of liquids). Special transport (such as yachts and trucks) can also be transhipped on containerships, but this takes place rarely.

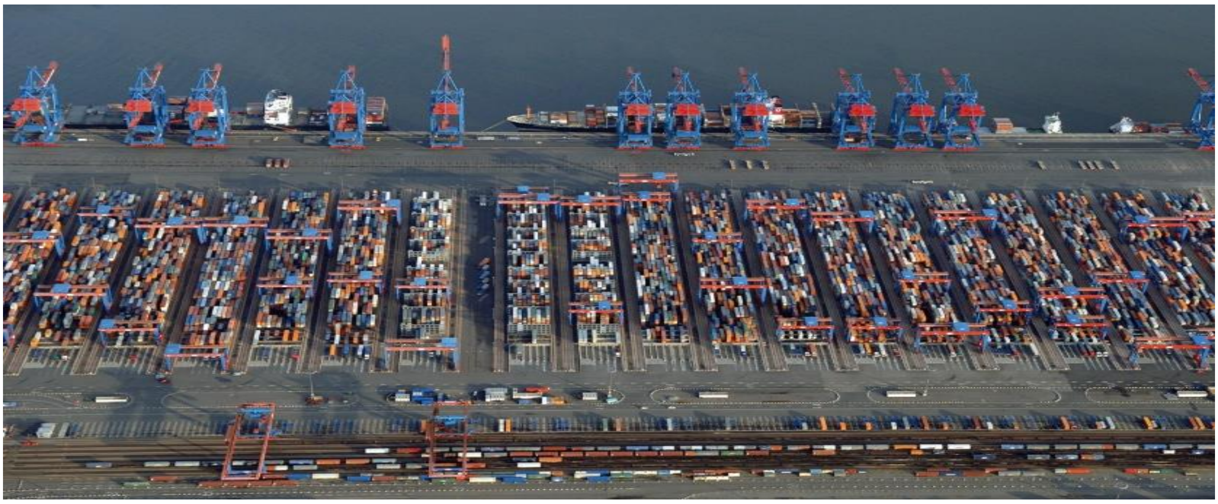

Figure 4: Overview of HHLA container terminal in Hamburg.
Source: ABB (2012)

1.1.2 Growth in container market

The number of worldwide handled containers increased continuously over the last decades, to 157 million TEU in 2012 (Clarksons, 2014). Looking to the world's largest container ports, Shanghai was world leader in 2012 with 32.53 million TEU (see Figure 5). Striking fact is that seven out of the ten largest container ports are located in China. The first European port - the Port of Rotterdam - is ranked 11th, closely followed by Hamburg (15th) and Antwerp (16th).

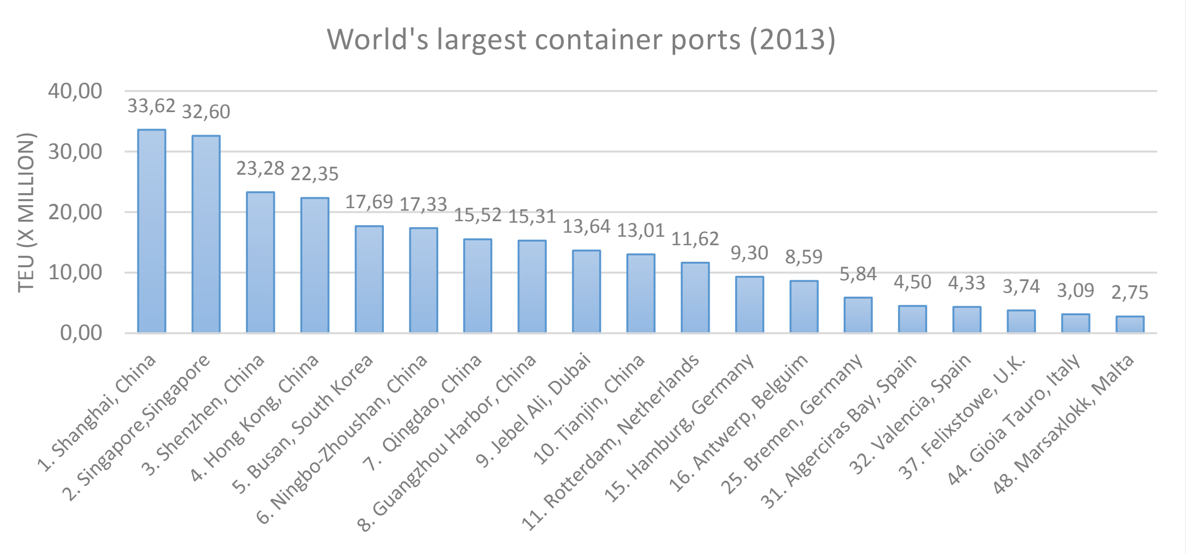

Figure 5: Position of European container ports in worldwide top-50 (2013)
Source: (World Shipping Council, 2014)

Compared to 2011, the number of handled containers of the 50 largest container ports has grown from 410 million TEU (2012) to 423 million TEU (2013), an increase of 3.1% (World Shipping Council, 2014). In 2012 the total worldwide transport of containers increased by 3.8% to 601.8 million TEU (UNCTAD, 2013).

Due to the increasing size of containerships, growth in handled containers and growing competition, container carriers demand higher handling speeds of their ships against lower prices per TEU (i.e. faster and cheaper). For container terminals, this leads to a continuous pressure to innovate. However, another driving factor of innovations are the (inter)national policies aiming to reduce the emission of greenhouse gases and the increasing availability of new (electrical) terminal equipment (more environment-friendly). These two aspects will be discussed in the next paragraph.

1.2 Reduction of greenhouse gases

In designing and improving terminal operations, container terminals need to operate within the legal boundaries, determined by governments on local, national and international level. Over the last decades more and more climate policies are unrolled, aiming to reduce greenhouse gas emissions. These policies directly affect container terminal performances (via governments and port operators demanding lower emissions) and indirectly (via container carriers and their customers who demand cleaner terminal operations to make their supply chain more sustainable). Driven by these policies, container terminals are stimulated to seek opportunities to lower their emissions. There are four main drivers for terminals to address the environmental impact of their operations (Geerlings, 1999):

1. leaner operations (e.g. skipping non-necessary activities and looking for optimisations)
2. transport via less damaging modalities (modal shift from trucks to trains/barges)
3. using new technologies (e.g. automatisation of processes)
4. change of behaviour (e.g. implementing rules of operation to change existing processes)

This paragraph presents the environmental policies and corresponding goals and elaborates on some of the four presented main drivers which contribute to a lower/better energy consumption.

1.2.1 Introduced climate policies

Over the last decades the issue of climate change gained a lot of attention. Although expert opinions differ on the level of influence humans have on the climate change, the fact that the human environmental footprint should be reduced gets worldwide consensus. In 1997, the United Nations adopted the Kyoto-protocol agreeing to reduce greenhouse gases by 2012 with an average of 5.2% compared to 1990; fifteen EU member states agreed to reduce their CO_2-level by 2012 with an average of 8% (United Nations, 1997). By the end of 2012 the Netherlands achieved a reduction of almost 10% (Compendium voor de Leefomgeving, 2013).

In 2012 an amendment to the Kyoto-protocol was adopted. In this amendment, new arrangements were made on the greenhouse gas reduction of participating countries. The Dutch government agreed to reduce their emissions with another 12% by 2020 (compared to 1990). This implies a total reduction of 20% between 1990 and 2020 (United Nations, 2012).

In addition to this worldwide agreement, the European Union offered to save another 10% (to 30% in total) if other major economies would make a proportional effort in reducing their emissions (European Commission, 2014). The Dutch government again added another 10% in their climate agenda by advocating a CO_2-reduction of 40% by 2030 (Ministerie van Infrastructuur & Milieu, 2013). The municipality of Rotterdam, provider of the largest European port, adopted the Rotterdam Climate Initiative which plead for a CO_2-reduction of 50% by 2025 (Rotterdam Climate Initiative, 2014).

1.2.2 Lowering emissions at container terminals

As introduced before, there are four main drivers for container terminals to address the issue of lowering greenhouse gas emissions (Geerlings, 1999). These four main drivers are discussed below:

Leaner operations

A relative easy way to influence the terminal's operations and its emissions is to analyse the terminal operations and to skip non-necessary activities. This can be achieved in several ways (Froese, 2014):

- minimising travelling distances at terminals;
- adapting operations to actual needs (e.g. optimising driving speeds and equipment performances);
- reducing consumption of terminal equipment (e.g. switching terminal equipment from active to idle state when possible and using more energy-friendly energy sources);
- optimising yard lighting (e.g. switching to LED and only illuminating necessary areas) and
- minimising energy consumption of reefers (e.g. sun-shading or temporarily turning-off power).

Results of research towards these subjects are discussed in paragraph 2.2.

Modal shift

In 2012 the transport sector was responsible for 29% of the Dutch energy consumption and 32% of the European energy consumption (Eurostat, 2012). To achieve the ambitious reduction of greenhouse gases, the transport sector could not stay unaffected. When comparing three modes for inland transport (road, rail and inland water transport), it is shown that the transport by barges and trains cause less pollution of CO_2. Barges reduce the emission (in kg. CO_2 per ton/km) with 45% compared to trucks. For diesel trains this reduction is 60% (CE Delft, 2011). National governments are trying to increase the transport by barges and trains in order to establish a reduction in CO_2.

The share of each modality is represented by the modal split, a percentage that reveals the total transported TEU*km per modality. In 2011 the modal split for the Netherlands I general was 49.3% by road, 44.6% by inland water transport and 6.1% by rail (Eurostat, 2011). To shift this modal split towards more transport by trains and barges, also known as modal shift, the European Union and Dutch government initiated several policies.

In their white paper on transport, the European Commission focused on a more sustainable transport system. By 2030 almost 30% of the road transport over 300km should shift to rail or water transport. By 2050 this percentage should be 50% (European Commission, 2011). To achieve a more sustainable port and especially to unburden the road network, the Port of Rotterdam agreed with the new container terminals on Maasvlakte 2 to change the modal split in the period until 2030. Compared with the modal split in 2012, the barge transport should increase from 35.3% to 45.0% and the rail transport should increase from 10.7% to 20.0%. The goal for road transport is to reduce the modal split from 54.0% to 35.0% (Port of Rotterdam, 2013). This modal shift implies serious effort for the twelve container terminals situated in the Port of Rotterdam to contribute to a reduction in greenhouse gases.

Availability of new technologies

Another development that led to a reduction of emissions at container terminals is the use of more environment-friendly energy sources by terminal equipment at container terminals. Where two decades ago most terminal equipment was powered by diesel, nowadays more and more equipment is powered by less polluting sources (e.g. biodiesel, hybrid systems or electricity[4]). This reduction of greenhouse gases goes hand in hand with increasing productivity, as could be seen at the ECT and APM terminals in Rotterdam.

In 2000 ECT introduced diesel driven AGVs and automated stacking cranes (ASCs) on their terminal. Instead of processing containers with straddle carriers, the AGVs led to a fully automated process without human interaction of drivers. The use of diesel was reduced because the equipment was driving more efficiently compared with human drivers. Meanwhile innovation led to the introduction of hybrid AGVs, which were introduced by ECT in 2012 (ECT, 2012). The next generation, fully electric AGVs, is announced by the new container terminal of APM Terminals at Maasvlakte 2. By 2015 the newest generation of battery-powered AGVs will be in operation (APM Terminals, 2012).

This example in the Port of Rotterdam shows the development of electrification that has been introduced in almost all terminal processes, allowing the state of the art container terminals to be fully electrified. Although the use of electricity is more environment-friendly, a challenge arises with regard to the way electricity is priced. This dilemma is addressed in paragraph 1.3.

Change of behaviour

A fourth driver is the change of behaviour at container terminals. New rules of operations, that change the currently used steering processes, might contribute to costs and or energy savings. The question that is addressed in this research – Is it possible to smoothen the energy demand by implementing new rules of operations? – is a good example. By changing the behaviour, i.e. the way in which operations are used to be executed, more awareness about the terminal operations can be achieved.

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[4] Despite some companies that state that the consumption of electricity (in kWh) is free of emissions, the production of electricity from renewable energy sources is only 4.4%. The major share is still derived from coal and gas, causing emission at power plants (CBS, 2012).

1.3 Pricing of electricity

Since more and more terminal processes are electrified, the electricity consumption of terminals rises. The electricity related costs are made up of two aspects (Autoriteit Consument & Markt, 2013):

1) fixed costs for connecting the terminal to the power network and
2) variable costs related to the (predicted and actual) consumption of electricity.

The fixed costs for connecting a container terminal to the power network consist of the initial investment costs for connecting the terminal to the power network and a yearly payment for the connection. The variable costs relate to the contracted transmission capacity (€/kW/year), highest peak demand (€/kW/month) and actual energy consumption (€/kWh).

1.3.1 Fixed costs

The hardware costs are fixed and determined by the electrical infrastructure of the terminal. The yearly costs depend on the costs related to the type of connection that is needed. For container terminals there are two feasible options: the so called 'medium voltage' (1-20 kV) and 'between voltage' (50/25 kV). A lower type of connection is only used for consumers, who have a relatively low energy demand and the two higher types are used for transporting electricity through the high voltage network (Autoriteit Consument & Markt, 2014). Out of the two feasible options, most container terminals will request a 'between voltage' connection, since the contractual transported supply is higher than 2,000 kW (Liander, 2014) (ABB, 2014).

1.3.2 Variable costs

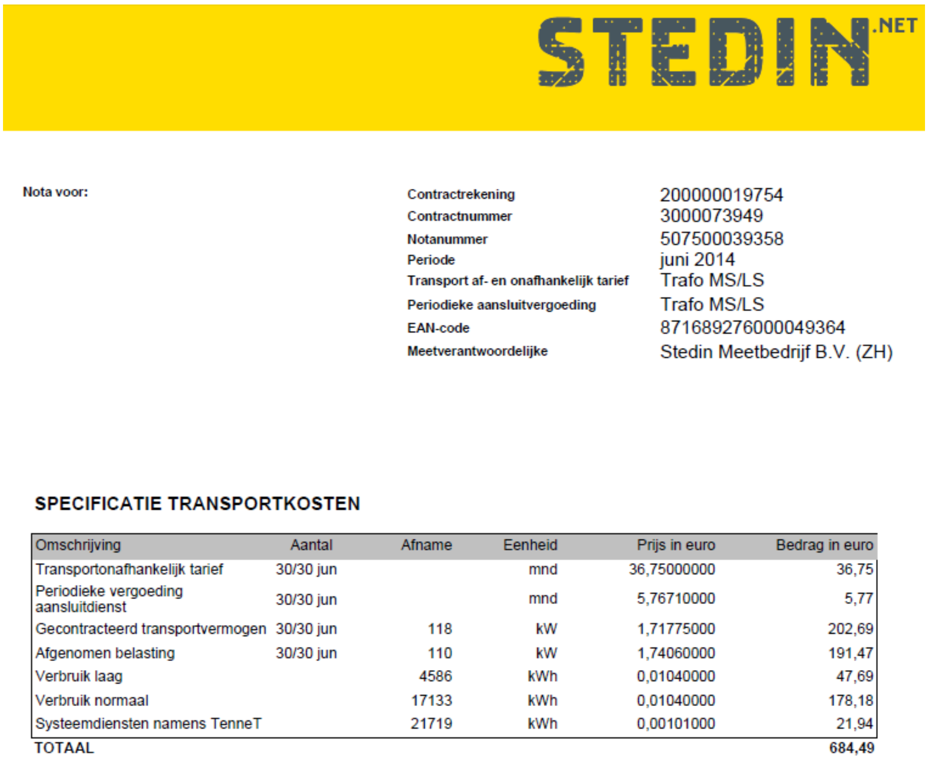
Besides the fixed costs for enabling the terminal to receive electricity, there are three aspects that determine the variable costs (Stedin, 2014).

1. The first aspect is the payment for actual energy demand (€/kWh/year), which is determined by measuring the actual power consumption over a certain period.
2. The second aspect are the transmission capacity costs. On forehand, container terminals need to present the height of their power demand, the so called contracted transmission capacity $(kW_{contracted})$. This demand is charged per year $(€/\,\mathrm{kW_{contracted}}\ /year)$. When the predetermined contracted demand differs too much from the average actual demand, the electricity supplier will charge the costs based on the actual demand.
3. The third aspect is then the charge for peak demand. The container terminals are charged for the highest peak demand that is observed over a year $(\frac{\mathrm{kW_{max}}}{year})$, even while this maximum is only achieved during a fraction of a second. Officially the peak is charged per month, but the policy of the grid exploiters is to charge peaks not only for the month in which it occurred, but to charge the peak for the next twelve months. To illustrate this: if in January the highest peak is 2,000 kW, the terminal will have to pay 2,000 times the monthly tariff per kW for the rest of that year. However, if the highest peak in March is 2,500 kW, the payment will be adjusted to 2,500 the monthly tariff for the next twelve months, until February the next year. In this way energy suppliers are charging companies for their peak demand because the peak demand is almost always higher than the requested contractual demand (i.e. $kW_{max} > kW_{contracted}$), which means that the energy suppliers could not prepare their energy production for this extra demand. Although this does not lead to big problems (the energy supply in the Netherlands is almost always sufficient to satisfy the energy demand), the energy suppliers do charge the unpredictable peaks.

1.3.3 Relevance for container terminals

Container terminals are able to influence the variable aspect of their monthly energy bill. Next to more energy efficient measures that reduce the actual energy consumption in kWh, the main challenges for container terminals are to achieve a steady power demand (enabling terminals to predict their contracted transmission capacity more accurate) and to reduce their peak demand as much as possible (especially because the highest peak is charged for the next twelve months). This lower peak demand will not lead to a lower total energy consumption or lower emissions, but will only save costs due to the pricing of peak demand.

For a container terminal, the costs related to the peak demand can count up to 25% of the total energy bill of a terminal (ABB, 2014). A standard test calculation of the Dutch grid operator Stedin (see Figure 6 on page 15), shows a peak cost percentage of even 30% of the total energy bill. Stedin charges peaks for almost €27 per kW per year (i.e. €2.2445 per kW/month), which shows the opportunity for container terminals to save costs when their peak demand is reduced. Halving the peaks can reduce the total energy bill with approximately 12.5-15%, which yields a container terminals tens of thousands of euros per month (MSC Terminal Valencia, 2012).



Nota voor:

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Contractnummer 3000073949
Notanummer 507500039358
Periode juni 2014
Transport af- en onafhankelijk tarief Trafo MS/LS
Periodieke aansluitvergoeding Trafo MS/LS
EAN-code 871689276000049364
Meetverantwoordelijke Stedin Meetbedrijf B.V. (ZH)

SPECIFICATIE TRANSPORTKOSTEN

Omschrijving	Aantal	Afname	Eenheid	Prijs in euro	Bedrag in euro
Transportonafhankelijk tarief	30/30 jun		mnd	36,75000000	36,75
Periodieke vergoeding aansluitdienst	30/30 jun		mnd	5,76710000	5,77
Gecontracteerd transportvermogen	30/30 jun	118	kW	1,71775000	202,69
Afgenomen belasting	30/30 jun	110	kW	1,74060000	191,47
Verbruik laag		4586	kWh	0,01040000	47,69
Verbruik normaal		17133	kWh	0,01040000	178,18
Systeemdiensten namens TenneT		21719	kWh	0,00101000	21,94
TOTAAL					**684,49**

Figure 6: Test calculation of Stedin (2014)

1.4 Research design

1.4.1 Problem statement

The first paragraphs of this chapter described the development of the containerised transport and today's challenges for container terminals. Despite the economic crisis, terminals face a growing container market with increasing capacities of containerships and growing competition between shipping companies. In order to satisfy shipping companies and to retain their competitive position, container terminals need to increase the handling speed of containerships and minimise the corresponding costs (goal: cheaper and faster). On the other hand, the propagated climate policies of several governments and port organisations challenge container terminals to reduce their greenhouse gas emissions (goal: more environment-friendly). A 'greener' image is becoming more and more important for terminals, since major companies (e.g. Walmart) are focussing on reducing the emissions in their supply chain and are therefore requesting low emissions from the container carriers that are transporting their goods and from the container terminal that is operating their containers (Port of Rotterdam, 2014).

Stimulated by the environmental policies of governments, the growing pressure from clients to increase handling speeds and lower emissions, container terminals feel a growing need to innovate and become more efficient. Over the last years, this led to the entrance of more and more electrical terminal equipment, which is not only more efficient, but also more environment-friendly than the replaced diesel-driven equipment.

However, the high pressure of carriers to handle the containerships as fast as possible leads to more electrical-driven terminal equipment that is operating at the same moment, potentially causing high peaks in energy demand. Because the peak demand is charged separately (see paragraph 1.3), the peak-related costs are responsible for 25-30% of the total electricity costs (ABB, 2014) (Stedin, 2014). This means that when the requested higher handling speeds of ships are obtained by operating more terminal equipment at the same time, this results in higher handling costs. Because carriers request both higher handling speeds and lower handling costs, this means that terminals have to look for new rules of operation, which are able to reduce the peaks in electricity demand while maintaining high handling speeds.

1.4.2 Research objective

The research objective describes the goal of the research and is derived from the problem statement in paragraph 1.4.1. The focus on environment-friendly innovations leads towards more and more terminal equipment that is powered by electricity. However, the use of many electricity powered terminal equipment causes peaks in energy demand when several energy intensive processes are executed at the same moment.

The smoothening of energy demand (also known as peak shaving) of electricity demand is therefore a good opportunity to save costs. However, the peak shaving might lead to extra handling time of a containerships, because the number of terminal equipment and processes that are operating at the same moment might get restricted.

The research objective is therefore:

> *"To investigate the possibilities for peak shaving the electricity demand at container terminals by applying new rules of operation for electricity consuming terminal processes, while monitoring the consequences for the handling speed of containerships."*

Scientific relevance

Over the last years many studies have been executed towards the energy efficiency of container terminals, resulting in models that describe the total emissions over a given time interval, mostly per year (see chapter 2). However, there is no study available that presents a model that determines the energy consumption of (electrical) terminal equipment per second to enable a visualisation of the peak demand. The first contribution to science is therefore to develop a consumption model that visualises the energy demand over time (in kW/s). This consumption model is not only valid for container terminal equipment, but can be applied for all sorts of electrical equipment in other industries that have the same characteristics (e.g. cranes).

After developing the consumption model, a simulation model can be constructed to enable a representation of a container terminal and to test process improvements (further called: rules of operation) that might reduce the peak demand as much as possible in order to decrease the corresponding (high) costs. The second contribution is therefore to present rules of operation that contribute to the reduction of peak demand at container terminals.

Business relevance

Today's state-of-the-art container terminals have introduced fully electrical terminal operations. With more and more electrical terminal equipment, the use of electricity rises. However, the transition from diesel-driven operations to electrical-driven operations satisfies the terminal operators, especially because the greenhouse gasses are reduced. However, the pricing of electricity (see paragraph 1.3) has shown the high costs of peaks in the electricity demand. Leading to 20-30% of the total energy related costs, a lower peak demand could save terminals thousands of euros per month (MSC Terminal Valencia, 2012). New rules of operation could contribute to reduce these peaks and would made container terminals aware of this problem and the potential savings.

1.4.3 Research questions

Based on the research objective (see paragraph 1.4.2) an academic research is developed. This research is executed by answering the main research question, which is decomposed into several sub-questions.

Main research question

The main research question that is addressed in this research is:

> *"What are the possibilities for reducing the peak demand of electricity consuming terminal equipment (peak shaving) in order to reduce the electricity related energy costs?"*

Sub-questions

The main research question can be decomposed into the following sub-questions:

1. What are the findings of earlier academic research towards the energy performance of container terminals? (chapter 2)
2. Which terminal processes determine the (electrical) energy consumption of container terminals? (chapter 2)
3. Which rules of operation (i.e. peak shaving strategies) can be developed to reduce the peak demand of terminal equipment? (chapter 2)
4. Is it possible to develop a consumption model that visualises the electricity consumption over time? (chapter 3)
5. Which data is needed to apply the developed consumption model? (chapter 3)
6. How does the peak demand look like when applying the consumption model for an existing container terminal? (chapter 3 and 4)
7. Which opportunities can be recommended for peak shaving the electricity demand of container terminal operations and what are the corresponding costs and (dis)advantages? (chapter 4)

These research questions form the basis for the methodology that is developed to execute the research (see next paragraph).

1.5 Research methodology

1.5.1 Research approach

The research approach describes the methodologies that are used to answer the presented research questions (see paragraph 1.4.3) in order to achieve the research objective. The research aims to gain more insight in the peak demand for electrical terminal equipment. In general this research is made up of an extensive literature study, the development of a consumption model and finally the development of a simulation model as a case study to test new rules of operation that might reduce the peak demand at container terminals, leading to recommendations that contribute to the peak shaving of the electricity demand at container terminals. The research approach is described more elaborately below.

After the introduction – which presents more understanding of the position of the containerised transport – the problem statement is introduced. Based on the problem statement a research objective and research questions are formulated. To gain a more detailed understanding of the problem, an extensive *literature review* is executed towards the environmental policies, energy consumption of container terminals and relevant terminal processes. This summarises earlier research and generates an overview of relevant processes that need to be included in monitoring the energy demand of container terminals (sub-question 1 and 2). Also the potential rules of operation that can be implemented to reduce the peak demand are presented (sub-question 3).

Based on the knowledge gap that is identified at the end of chapter 2, a consumption model is developed to determine the energy demand (kW/s) of electrical-driven terminal processes. This creates a deeper insight in the volatile energy consumption of container terminals and the data that is needed to represent this energy consumption over time (sub-question 4 and 5). The relevant processes of the consumption model are then applied in a case study for an existing container terminal. Due to the dynamic aspect of the energy consumption and the need to test new rules of operation that might contribute to lowering the peak demand, a simulation model will be constructed for this purpose.

After the model has been validated with real data and expert opinion, the model can be used to test the earlier developed rules of operation (sub-question 6 and 7). For every new rule, the advantages and disadvantages are presented, resulting in conclusions that show which (combination of) rules of operation are most effective and feasible. The research is finally concluded by giving recommendations and directions for further research and by reflecting on the current research.

1.5.2 Thesis outline

The thesis outline is visualised by a research flow diagram (see Figure 7). The research flow diagram visualises the research process and shows the steps where literature, expert opinion and/or data is needed (Verschuren & Doorewaard, 2010). The white blocks represent the main processes, from problem statement to conclusions and recommendations. The coloured blocks serve as input for several processes and represent the needed sources. The diagram can be seen as thesis outline, considering the fact that the steps are categorised per chapter.

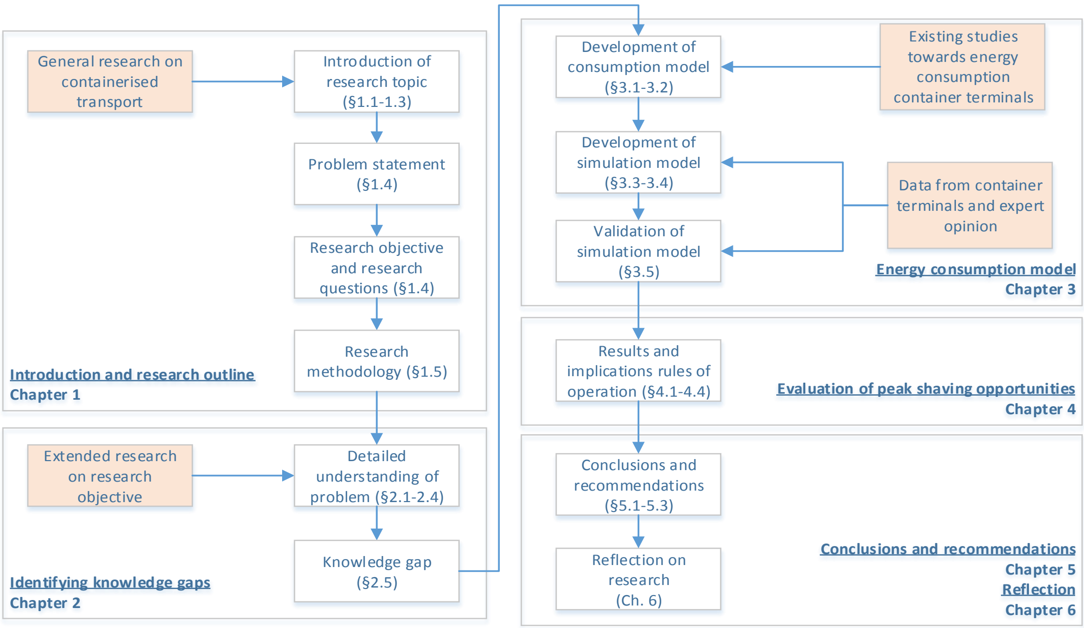

Figure 7: Research flow diagram with main research processes (white) and data input (coloured)

1.6 Conclusion

The growing size of containerships and increasing annual worldwide transport of containers has stimulated container terminals to make their processes more efficient and to focus on higher handling speeds and lower handling costs. Stimulated by governmental policies aiming to reduce the greenhouse gas emissions (mainly focused on CO_2), more and more electrical-powered terminal equipment is introduced. Although the total emissions are reduced by this development, a dilemma occurs when the need to increase handling speeds leads to more simultaneously operating terminal equipment and higher peaks in electricity demand. Because of the charged costs for these energy peaks – leading to 25-30% of the total energy bill (ABB, 2014) (Stedin, 2014), peaks have to be prevented as much as possible.

An energy-related cost reduction for a container terminal might lead to an increased handling time of a containership. When applying new rules of operation that reduce the peak demand, the trade-off between the (higher) handling time of a containership and the (lower) costs related to a lower peak demand has to be monitored in order to weigh the effects of both performance indicators.

In order to investigate the peak demand at container terminals, more insight is needed into the terminal processes and corresponding energy-consuming elements. This question is addressed in chapter 2.

Containership ZIM Rotterdam entering the Yangtze port in Rotterdam
Photo: Hans Elbers (Fotovlieger.nl, 23 February 2014)

2. Container terminal operations

The main research question (presented in chapter 1) suggests to develop an energy consumption model that can be used to visualise the energy consumption of a container terminal over time and which forms the basis for a simulation model that enables the testing of newly developed rules of operation to reduce the peaks in electricity demand at container terminals. But in order to develop such a consumption model, first more understanding is needed about the operations and energy consumption of container terminals.

This chapter starts with an exploration towards the terminal processes to get a broader understanding of the operations that take place at a container terminal (paragraph 2.1). After that, paragraph 2.2 discusses earlier (scientific) studies towards the sustainability of container terminals. In paragraph 2.3 the volatility of a terminals' energy demand is visualised, followed by the development of rules of operation that contribute to a lower peak demand (paragraph 2.4). These first four paragraphs lead to the formulation of the knowledge gap in paragraph 2.5. The chapter is concluded in paragraph 2.6.

2.1 Exploration of terminal processes

In order to get a more comprehensive view on the energy consumption of container terminal, the general terminal operation will be decomposed into processes to enable a better understanding of all (energy-consuming) movements at terminals, which increases insight in all elements that influence the energy consumption. The container handling processes at terminals are described by inter alia Vis & De Koster (2003), who give an overview of all processes related to the transhipment of containers at container terminals. In general six handling processes can be distinguished: the arrival of the ship, (un)loading of the ship, transport of containers between stacking area and quay cranes, (un)stacking of containers, inter-terminal transport and other modalities (see Figure 8 and Figure 9). These six processes are described in paragraphs 2.1.1-2.1.6. In paragraph 2.1.7 the remaining terminal processes are described shortly.

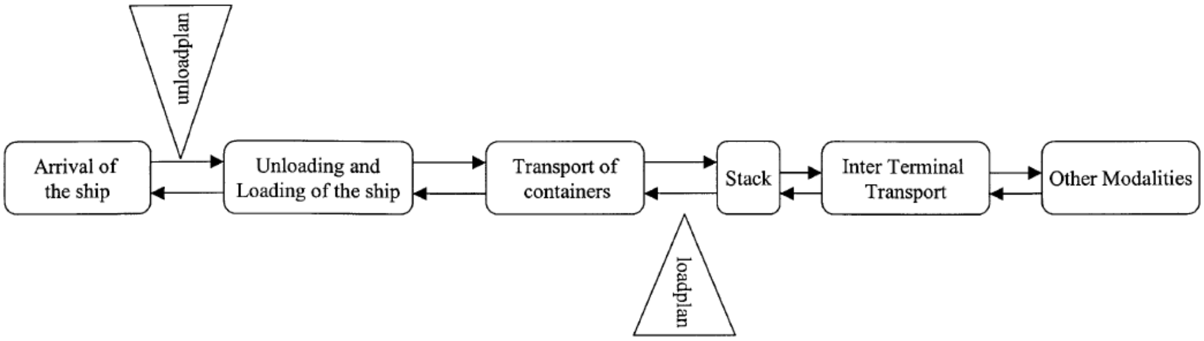

Figure 8: General process outline for handling containers at container terminals
Source: (Vis & De Koster, 2003)

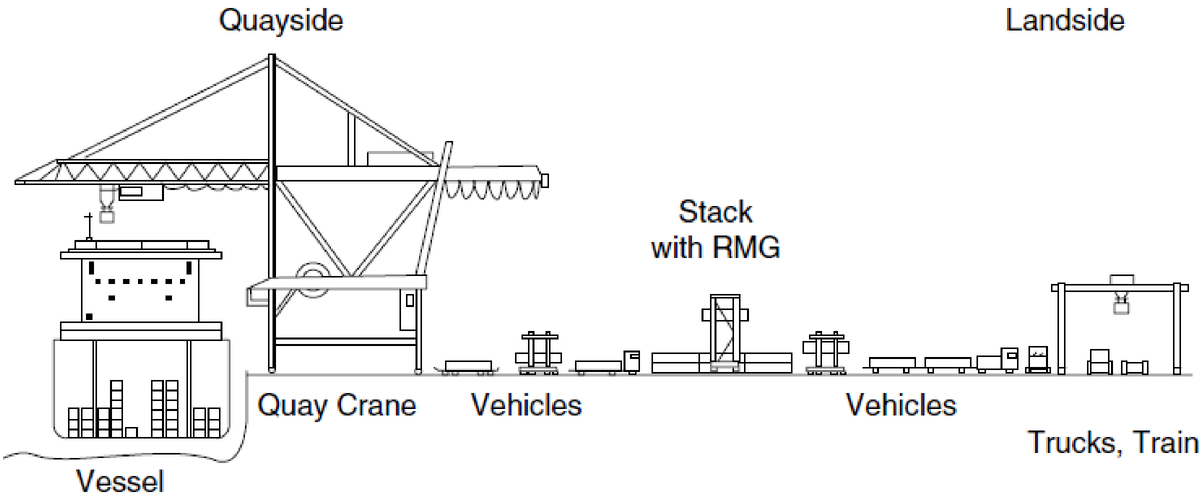

Figure 9: Schematic side-view on container terminal operations
Source: (Steenken, Voß, & Stahlbock, 2004)

2.1.1 Arrival of the ship

Before the ship arrives, the terminal must reserve a berthing place for the handling time that is expected for the incoming containership. Based on the vessel attributes of incoming ships (vessel code, length, depth and width) and handling plan (pre-arrival and pre-departure time, expected number of handled containers and expected) a berthing place is allocated (Sun, Sun, & Yang, 2009). The allocation of berthing places can be done in different ways. One strategy is to minimize the time ships are docked at the quay side. Containers are then handled by the 'first come first serve' principle. Another strategy would be to moor a ship close to the stacking area where most of the containers are located that need to be loaded on this ship. Despite the beneficial influence on the minimisation of total transport distance of containers, this strategy could be detrimental for the average waiting time which will likely dissatisfy container carriers (Imai, Nagaiwa, & Tat, 1997).

2.1.2 (Un)loading of containers

After the ship has been moored, the quay cranes and barge cranes are able to unload the incoming containers based on the unloading plan. For loading and unloading containers, ship-to-shore cranes (or barge cranes in case of barges) are used. Quay cranes usually use a normal spreader for transferring a container, which enables them to handle one container at the same time. Quay cranes which possess a more advanced spreader can handle more containers at the same time (e.g. the twin-lift and tandem-lift) (Stahlbock & Voß, 2008). The Super Post Panamax quay cranes, the currently standard cranes for unloading the largest containerships, are able to make approximately 32 lifts per quay crane per hour (APM Terminals, 2014). This allows a quay crane to handle 32-64 TEU per hour with a normal spreader and up to 128 TEU per hour with a tandem lift spreader.

The handling capacity of a container terminal is highly dependent on the number of quay cranes and their capacity, because the cranes determine the handling time for a ship as well as the throughput of containers to the stacking process (Eugen, Şerban, Augustin, & Ştefan, 2014).

During the (un)loading of a containership (i.e. stowage), two criteria are important: the ship's stability and number of unproductive moves (Imai, Sasaki, Nishimura, & Papadimitriou, 2006). While (un)loading, the ship's stability changes due to the continuously changing container load. Because containerships visit several container terminals, each of them unloading containers from and loading containers to the ship, not all containers which have to be unloaded are positioned on top of the ship's stacks. The ships have therefore to be loaded in an efficient way, allowing the next container terminal to unload them with a minimum of unproductive moves. These two criteria are often in conflict, because the most efficient loading (regarding the minimisation of unproductive moves) might not also be in line with the most efficient loading regarding the ship's stability. This makes the stowage very complex (Bortfeldt & Gehring, 2001) (Steenken, Voß, & Stahlbock, 2004) (Dekker, Voogd, & Van Asperen, 2006), especially because the stowage plans have to be aligned over all different ports that have to (un)load the ship (Wilson & Roach, 2000).

Quay cranes are connected to the electricity network. For all quay crane processes (moving of crane and spreader, crane lighting and auxiliary processes) electricity is supplied by the network. For the lowering of a container power is even regenerated and returned to the power network. However, the energy consumption for lifting a container is higher than for other crane movements (see chapter 3.3 for a more detailed description of this energy demand).

Figure 10 and 11 : A twin lift spreader (left) with a capacity of two 20 ft. containers and a tandem lift (right) with a capacity of two 40 ft. containers. Source: Port Strategy (2007 & 2009).

2.1.3 Transport of containers

The third process is the transport of containers between the stacking area and quay cranes. First, incoming containers are unloaded from the ship and then placed on a vehicle on the land side, which brings the container to the right stacking row in which the container later will be placed. For this transport several types of equipment are deployed (e.g. automated guided vehicles, reach stackers, terminal trucks or straddle carriers), with different energy consumption specifications. AGVs are driven by diesel, hybrid systems or fully electric via batteries. The current terminal trucks, straddle carriers and reach stackers run on (bio)diesel. In the future these types of equipment might also be available on fully electric. The determination which type of transport is used and how many vehicles are needed to handle the daily operations is important for terminals (Vis & De Koster, 2003), because too much equipment increases the equipment costs for container terminals and insufficient equipment increases the handling time for container carriers.

2.1.4 Stacking of containers

Containers arrive at the stacking area at so called input/output points, I/Os, where containers enter the stacking area from the quay side and landside or leave the stacking area to one of these sides (Carlo, Vis, & Roodbergen, 2014). Based on a survey of 113 container terminals worldwide, the most frequently used stacking cranes are the rubber-tired gantry cranes (RTGCs, 63%), straddle carriers (20%) and rail-mounted gantry cranes (RMGCs, 6%) (Wiese, Kliewer, & Suhl, 2009). The RTGCs are mainly seen in Asia, where the straddle carriers and RMGCs are mostly used in Europe. The RMGCs are currently known as automated stacking cranes (ASCs), which operate without human interaction (Carlo, Vis, & Roodbergen, 2014). RTGCs run on diesel and have a generator to convert diesel to electricity for controlling the spreader. The ASCs are connected to the electricity network, just as the quay cranes.

Restacking

Besides the stacking activities of incoming and outgoing containers, containers are also moved to another stack to support a smooth loading and unloading of containers. This is the case when for example a container which is stacked below another container is needed first. Then the above piled container(s) can be restacked to enable a smoother transport of the needed container. Each move that is made to release a lower stacked container is called an unproductive move. Container terminals try to minimise the number of unproductive moves because these movements are time-consuming and costly without having a directly added-value.

Reefers

Temperature-controlled containers, known as reefers, are placed in special parts of the stacking area where electricity plugs are available. The reefers are (un)plugged manually by reefer mechanics. The method which is used to build this schedule has a major influence on the productivity of the reefer mechanic (Hartman, 2012). In general the reefer mechanic receives a job from the terminal operation system (TOS). The mechanic walks or drives to the specified reefer stack and (un)plugs the container, after which the mechanic confirms the completion of the job so the TOS knows that the mechanic is available. The challenge is to balance the minimised weighted sum of idle time and total travel time (Hartman, 2012).

Because of the fixed position of the reefer stacks, the terminal operations are highly influenced by the size and position of the reefer stacks. After testing several terminal layouts (including reefer stacks) the distribution of reefer stacks over the whole stacking area of a terminal was proven to be more efficient than the currently used centralised layout, where all reefers are stacked together (Choi, et al., 2004).

2.1.5 Inter-terminal transport

The inter-terminal is also known as the landside transport and deals with the transport between the stacks and the loading area for trucks or trains (see Figure 9, page 19). This transport can be executed by multi-trailer trucks (which are able to transport multiple containers at once) or AGVs, but also by straddle carriers or reach stackers, depending on the loading process of containers on trucks and trains. When there is a separate crane terminal for (un)loading these modalities, the containers need to be transported to the cranes in order to be picked up and loaded on the train. This can be done with multi-trailer trucks or AGVs. For using multi-trailer trucks, the challenge is to minimise the number of empty trips and trailers (Vis & De Koster, 2003).

If no separate (un)loading terminal exists, the containers can be picked up at the stacks with equipment that is able to load the trucks and trains, or vice versa. This can be done with for example straddle carriers and reach stackers.

Next to the transport between the trucks/trains and stacking area, there is another need for transport of containers within the terminal area: the reorganisation of containers. This is for example needed if empty containers in the stacking area are appointed for transport to the empty container depot or to the maintenance workshop or when a container needs to be re-stacked in another part of the stacking area (Steenken, Voß, & Stahlbock, 2004).

2.1.6 Other modalities

As already presented in paragraph 2.1.5, there are two possibilities for (un)loading containers at the landside of the terminal. The first possibility is a separate terminal which is responsible for (un)loading containers on/from trucks and trains. Often this is done by gantry cranes, which are flexible to move above the trucks and trains.

If a terminal does not have a separate rail terminal, the loading can be done by the terminal equipment which has picked up the containers at the stacks (e.g. reach stackers or straddle carriers). These types of equipment are able to load the containers directly to the trucks and trains, or unload them from these modalities.

2.1.7 Other processes

Besides the movement of containers, several other elements contribute to the energy consumption of container terminals. The reefers and terminal lighting are responsible for the major part of energy consumption of the remaining processes (see also paragraph 2.2). Other consumption is contributed by premises (e.g. buildings, IT-facilities, offices), workshops, off-yard processes (e.g. empty storage facilities) and other services like freight stations.

An important element to mention is the terminal layout, which determines the equipment that can be used and influences the distances between all locations (e.g. the distance between quay and stacks and between stacks and in-land cranes for (un)loading on other modalities). The layout is therefore (indirectly) an influencing aspect of the container terminal consumption. A change in terminal layout could save up to 70% of its CO_2-emissions. Using smaller widths per stacking block, the terminal performance increases, but this also increases the corresponding costs (Wiese, Suhl, & Kliewer, 2011).

2.2 Energy consumption of container terminals

2.2.1 Development of innovations

The energy consumption of container terminals is something that container terminals did not worry about for a long time. Until a couple of years ago their main focus was to maximise productivity in order to satisfy the demand of their customers, the container carriers. Their goal was to increase the terminal's storage capacity and handling speeds of containerships. Over the last decades different studies are executed towards the question how the productivity could be increased. In the 1980s a research concluded that advanced computer communications and control technology would become very important strategies to improve the productivity and reduce investments (Leeper, 1988). In the 1990s a research was executed towards the use of information technology (IT) at the Port of Singapore Authority, showing that the use of IT leads to cost reduction and better customer-service (Wan, Wah, & Meng, 1992). The general opinion was that more intelligent operation systems could support the growth in productivity.

Because of the continuing worldwide growth in handled containers and capacity of sea vessels (see Figure 2, chapter 1), terminals faced the challenge to meet even higher productivity standards. Important innovations that contributed to this challenge were the automated guided vehicles (AGVs) and automated stacking cranes (ASCs). The general principle, automated guided transporters, was already successfully applied in other industries for decades, but the container terminals introduced the AGVs in 2000, later followed by more automated transporters like the ASCs (Grunow, Günther, & Lehmann, 2005).

While container terminals focussed on increasing their productivity and handling speeds, more than 180 countries agreed to sign the Kyoto-agreement, in which they agreed to lower their national greenhouse gas emissions (United Nations, 1997). A development that would impact the container terminals business in two ways: 1) by national and local policies willing reduce the emissions in their area and 2) by container carriers and their customers demanding lower emissions of activities in their supply chain in order to achieve a greener image. This development set new goals for container terminals. Improving the terminals productivity alone was not enough, but reducing the terminal's emissions became an important issue.

Because the emission of greenhouse gases is largely determined by the production and consumption of fuels and electricity, the overall energy consumption needs to be reduced. This change does not per se imply a disadvantage for container terminals. In a research towards sustainability at Hutchison Port Holding (owner of almost 50 ports worldwide) was shown that there is a positive relation between the use of green management practices (existing of cooperation with supply chain partners, environment-friendly operations and internal management support) and firm performance (e.g. cost reduction) (Lun, 2011).

2.2.2 Research on emission of container terminals

The (inter)national policies on sustainability brought researchers to the question to make an estimation of the energy consumption and corresponding greenhouse gas emission of ports and container terminals. Until that moment, earlier research focussed on increasing productivity (see last paragraph), which made the issue of energy consumption of ports and terminals relatively new.

At this moment, a broad range of studies have been executed to make an estimation of the port and terminal emissions. An example is the attempt of Zamboni et al. (2013) to calculate the fuel consumption and exhaust emissions of heavy duty vehicles (HDV) in port areas. This can be done by categorising the potential traffic flows and vehicle types, followed by defining the different port activities that take place. With the information of logistical companies and vehicle characteristics, an estimation can be made of the emissions of HDVs.

To gain more understanding of the emissions at container terminals, Geerlings & Van Duin developed a deterministic methodology, based on the graduation thesis of Van der Voet (2008), to calculate the energy consumption of terminal equipment (Geerlings & Van Duin, 2011) (Van Duin & Geerlings, 2011). The conceptual model shows the relevant factors that influence the consumption of fuels and electricity (see Figure 12 on page 24). Important factors for determining the total energy consumption are the average distance per container movement, total container throughput and terminal configuration. The research shows that diesel-powered equipment is largely responsible for the total CO_2-emissions at terminals. This is largely caused by the terminal layout, which influences the length of movements for terminal equipment. New designs of current terminal layouts could save up to 70% of the current emissions. The two suggested alternatives to achieve this reduction are the minimisation of the total distance covered by diesel-generated equipment and mixing the currently used diesel with biofuels. The research did not include the energy consumption of reefers, terminal lighting and other energy consumption (e.g. buildings, workshops etc.); at least it was a valuable attempt to achieve more insight in the energy consumption of container terminals.

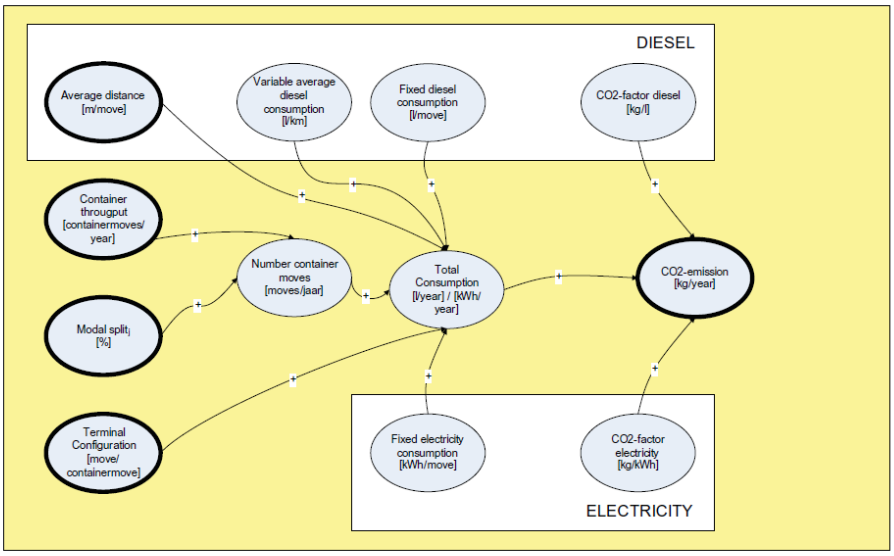

Figure 12: Conceptual model for determining energy consumption of terminal equipment
Source: (Van der Voet, 2008) (Van Duin & Geerlings, 2011)

In further research an attempt was made to gain more understanding of the energy consumption of the other processes, like for example the reefers. A first exploratory study to estimate the energy consumption and corresponding CO_2-emission of reefers at the Port of Rotterdam showed an annual electricity consumption of 80-189 million kWh, equal to a CO_2-emission between 49.9 and 117.9 kilotons (Heij, 2012). Converted to the emission per container, this is between 4,158 and 9,825 kg. CO_2 per reefer per year (with reefers having an average stay of 5.3 days). Where the total energy consumption of all container terminals was estimated at 140 kiloton CO_2 (Geerlings & Van Duin, 2011), reefers would be responsible for 35% - 80% of the total energy consumption.

Based on the energy consumption of the Noatum Container Terminal in Valencia (NCTV) during 2011 and 2012, the electricity consumption of container terminals was calculated (GreenCranes, 2013). The consumption of reefers is estimated at approximately 45%, crane movements at 35%, energy consumption of buildings at 15% and finally the yard lightning at 5% (see Figure 13). The other terminal processes (e.g. terminal trucks, rubber-tired gantry's and straddle carriers) are powered with (bio)diesel and are therefore not included in this graph.

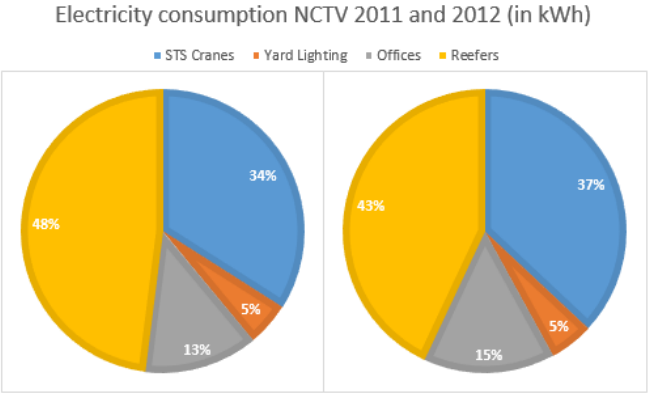

Figure 13: Overview of electricity usage at Noatum Container Terminal in Valencia
Source: (GreenCranes, 2013)

The referred studies in this paragraph are a first estimation of the energy consumption at container terminals and mark the beginning of a process towards a better academic understanding. Although terminal operators know the energy consumption of their terminal in detail, they are reluctant to share this information as they fear competitive disadvantages. The academic researchers are therefore still dependent on deterministic calculations. It might be expected that the accuracy and scope of academic research will increase and estimations will come close towards the exact energy consumption.

2.3 Dynamics in electrical energy consumption

As discussed in earlier paragraphs, the energy demand over container terminals is very volatile. Processes like terminal lighting and energy consumption of buildings are quite constant over time. The deployment of terminal equipment leads to a more dynamic energy demand. Not only because most terminal equipment is only operating when a ship arrives and new containers need to be handled, but especially because of the different energy demand for different movements that are executed by terminal equipment (see chapter 3 for a deeper discussion of the energy demand per movement).

The energy demand of a terminal in one week can be seen in Figure 14. The figure shows the high volatility for a small terminal. The values for the vertical axis are deleted because the data is relatively outdated and is not comparable with the current standards. However, the dynamic pattern of energy demand as shown in Figure 14 can still be found at modern container terminals (ABB, 2014).

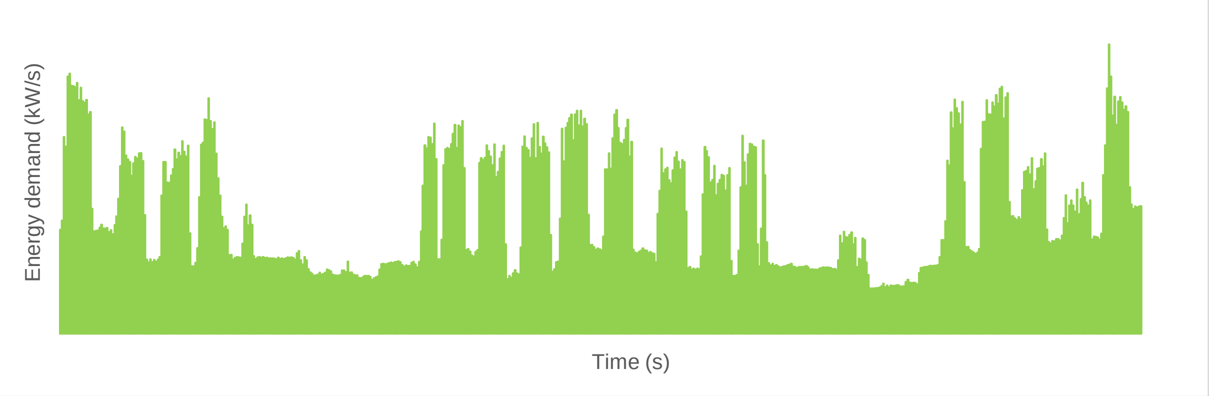

Figure 14: Energy demand container terminal during one week (ABB, 2014).

2.4 Rules of operation

2.4.1 Peak shaving developments

The peak shaving measurements, also referred to as rules of operations are developed to reduce the peak demand of a container terminal. The reduction of peak energy consumption is not something that concerns container terminals only. In several areas research is executed towards the peak shaving of electricity.

What strikes is that almost all organisations have a low awareness about their peak consumption, for example in hospitals. Prudenzi et al. (2009) discussed the urgency for hospitals to monitor their energy demand, since hospitals operate 24/7 and consume 2-3 times more energy than other institutional buildings.

Another industry that copes with this challenge is the loading of plug-in electric vehicles. When people come home they plug-in their cars. Some will use the car a couple of hours later, but others leave their car for the night until the next morning. When all cars start loading immediately, a huge peak in energy demand arises. In their publication, Masoum et al. (2010) show the influence of smart-load management on the peak demand. In this way car owners can designate preferred charging zones, which enables the smart-load management system to determine which car is loaded at each moment in time to reduce the peak demand. The smart grids, technologies that are applied to control the energy demand on the electricity grid, are gaining more and more attention. The prediction of energy demand, real-time control and advanced planning are important aspects to control the energy demand and corresponding peak shaving (Molderink, Bakker, Bosman, Hurink, & Smit, 2010).

When electricity costs are much higher than gasoline or diesel, industrial companies consider the deployment of generators to temporarily switch the energy supply from the national grid operator to their own generator (Malinowski & Kaderly, 2004).

Existing research and papers show a wide variety on peak shaving measurements, whereby two aspects are most important: getting more insight in the energy consumption and smart strategies to control the energy demand and to spread the energy consumption of energy intensive processes over time.

2.4.2 Peak shaving measurements for container terminals

The rules of operation can be seen as measures that can be taken by container terminals to influence the peak demand of their container terminals. As concluded in last sub-paragraph, first more insight is needed in the energy consumption. Next to that, the implementation of a smart management system enables a company to reduce their peak demand. This system should contain strategies to spread the energy consumption over time (peak shaving).

As such, the developed consumption and simulation model in this research (see chapter 3) can be used to gain more insight in the energy consumption, where the application of rules of operation can be seen as smart management system.

In the simulation model two rules of operation are implemented:

1. Limitation of the number of quay cranes lifting at the same moment

   The first rule of operation, the restriction of the number of simultaneously lifting quay cranes, looks at what happens when not all operational quay cranes are enabled to lift containers at the same moment. A quay crane has two lifting 'movements' (see paragraph 3.4): the lifting of the spreader and container above the ship and the lifting of the (empty) spreader above the quay). When for example maximum four of the eight quay cranes is enable to lift at the same moment, no more than four quay cranes are enabled to process a container through one of the two lifting movements.

2. Limitation of maximum energy demand per second

   The second rule of operation deals with the maximum energy demand. This can be set at a certain kW-demand, to impose a maximum for all quay cranes. Before starting a new movement, every quay crane requests the energy that it is expecting to use (dependent on the movement and the container load). Based on this expected demand, the model looks whether this demand is available. If not, the quay crane is asked to pause, until there is enough demand left to start the movement. When quay cranes are asked to pause, they are queued in a first-in-first-out principle, which means that the quay crane that is waiting the longest, will be the first to get clearance to restart operations. It is assumed that quay cranes can only pause in between the six general movements. In the simulation model all general movements are divided into two or three sub-movements. However, stopping in between the sub-movements would costs so much energy, that the general principle behind this rule of operations would be undone.

The rules of operation are implemented in the simulation model to enable the experiments. The rules of operation are executed for two types of container terminals: a terminal with 6 operational quay cranes and a terminal with 8 operational quay cranes. This enables the comparison of the impact of the rules of operation for different container terminals.

The two rules of operation are tested to investigate their impact on the peak demand and handling time. As such, a rule of operation can be seen as (part of) a smart management system (see paragraph 2.4.1) to control the energy demand. Chapter 4 discusses the different results of these analyses. The results for each rule of operation will be compared with the current situation on two criteria:

- influence on the height of the electrical peak demand (in kW);
- influence on the average handling time.

2.5 Knowledge gap

Derived from the first paragraphs of this chapter, the knowledge gap deals with the dynamic visualisation of the energy consumption at container terminals. Based on the existing challenge to reduce the energy emissions, earlier research used a more deterministic approach to visualise the total energy consumption over time (in kWh/year or L/year). This resulted in several studies which, based on general assumptions, describe the energy consumption of separate terminal processes. However, there are three lacking elements in the existing approaches that form the knowledge gap:

1. Existing energy consumption models are not developed to visualise the energy consumption per second, which is needed to dynamically visualise the energy demand over time (in kW/s). A model that is able to do this is therefore developed in this research.
2. The container terminal business is faced with growing uncertainty (e.g. high competition, energy price uncertainty and geopolitical tensions) forcing them to make their operations more efficient, mainly achieved by cost reduction. To be able to reduce the energy related costs, first more insight is needed

in the energy consuming processes and opportunities that might contribute to a reduction. This research presents opportunities for reducing the peak-related energy costs of terminal equipment.

3. Grid operators calculate the electricity price for container terminals partly based on the peak energy consumption of terminals. The higher the observed peak, the higher the costs. The challenge for container terminals is therefore to smoothen their energy consumption over time to prevent high peaks in energy demand. However, it is unknown to what extent the peak demand can be reduced. This research presents to which extent this peak demand can be reduced.

Derived from these three missing aspects, the knowledge gap is how to develop a more detailed representation of container terminal processes that shows the dynamic energy demand of electricity over time in order to test the impact of different process innovations and possibilities for peak shaving of this energy demand.

2.6 Conclusion

The literature review in this chapter has analysed earlier executed research and showed the important processes which are responsible for a terminal's energy consumption. Earlier research (sub-question 1) has shown that the ongoing innovations towards terminal equipment led to more efficient container terminal processes and the use of cleaner energy sources like hybrid systems and electricity instead of diesel. However, the terminal layout is also highly responsible for the energy consumption and new layouts could save up to 70%. The earlier research is based on deterministic approaches with a focus on the annual energy consumption in kWh/year. There is no existing study known that represents the dynamic energy demand of complete container terminals in kW/s.

The processes that determine the energy consumption of container terminals (sub-question 2) can be divided into transportation processes and other processes. The transportation processes are the (un)loading of containers between ship and shore, transport of containers between quay side and stacks, the stacking of containers, inter-terminal transport between stacks and trains/trucks and finally the equipment used for (un)loading the trains and trucks. The other processes are the energy consumption of reefers, terminal lighting and buildings (e.g. workshops, offices, freight stations etc.).

Because existing studies do not visualise the energy consumption of a container terminal in kW/s, the peak demand cannot be visualised before developing an energy consumption model and subsequently a simulation model to visualise the energy demand over time and to analyse the peak demand. This chapter has presented all relevant processes that need to be taken into account for determining the energy demand of a container terminal, which forms the basis for the calculation model in the next chapter.

View on the Port of Rotterdam in morning light
Photo: Cees van der Wal (twitter.com/vdWalfotografie, 5 March 2014)

3. Energy consumption model

Chapter 2 showed that the energy demand at a container terminal is very volatile and dependent on peak productivity of terminal equipment. Existing studies towards energy consumption at container terminals mainly focused on the overall energy consumption. Because of the high costs of peaks in energy demand, it is necessary to develop a consumption model that shows the dynamics over time. This chapter presents an energy consumption model which is able to visualise this energy demand (kW/s) over time. Subsequently a simulation study is developed to identify the peak demand for an existing container terminal and to test to what extent the developed rules of operation contribute to a reduction in peak demand.

Paragraph 3.1 focuses on the development of a consumption model that takes into account all relevant aspects of electrical-powered terminal processes dealing with a dynamic energy demand over time. Processes with a steady energy demand (e.g. terminal lighting and buildings) will not be taken into account. Derived from this consumption model, an overview of required data is presented in paragraph 3.2. Based on the consumption model and required data a simulation model is applied for a case-study terminal in Valencia. The model development is described in paragraph 3.3, followed by a description of the model design in paragraph 3.4. After the model is validated in paragraph 3.5, the chapter is concluded in paragraph 3.6.

3.1 Development of consumption model

By developing the consumption model, it is important to identify all container terminal processes (see paragraph 2.1). Based on this overview an analysis can be made of all electricity-powered terminal processes. However, a distinction needs to be made between processes with a volatile energy demand and a steady energy demand. The steady processes do not have any influence on the occurrence of peaks, which is important to answer the main question of this research (see chapter 1.4). Therefore the steady processes are disregarded from now on. The energy consumption of reefers, which is influencing the peak demand because of its variable consumption over time, is also not included. The reason for this is that adding the reefer energy consumption would make this research too comprehensive.

Regarding the part of the terminal equipment consumption, the consumption model is partly based on the work of Van der Voet, who tried to create a deterministic insight in the energy consumption and carbon dioxide emissions of terminal equipment (Van der Voet, 2008). Van der Voets research was based on average distances on terminals and the average energy consumption per move, which was a valuable first attempt to create insight in the energy consumption of particular terminal processes and for specific terminal equipment.

In order to gain more understanding of the different terminal processes and energy consuming elements of these processes, the IDEF0 (Integrated DEFiniton) method is used to construct process schemes. This method will be explained in paragraph 3.1.1.

3.1.1 IDEF0

The IDEF0-schemes are part of the IDEF modelling language which is often used in systems engineering. The IDEF0 method represents the functions and its ICOMs: Inputs, Controls, Outputs and Mechanisms (Sage & Armstrong, 2000). As shown in Figure 15, on the left side of the scheme, an input enters the function/process box. The controls that are needed for the process (e.g. data) enter on the top side of the box. The mechanisms (entering from below) show the means needed for executing the process (e.g. machines or operators), which is of interest because these mechanisms are responsible for the energy consumption of the corresponding process. When the process is ‘executed’, outputs are leaving at the right side.

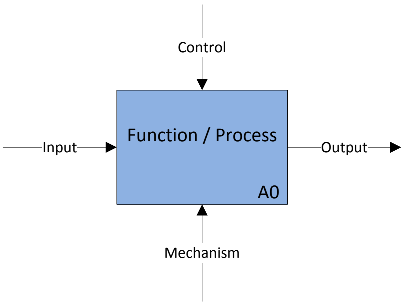

Figure 15: IDEF0 process scheme

The IDEF0-method enables construction of models with a top-down representation, but which are built on bottom-up processes. This is done via decompositions of general processes. Although the IDEF0-method was not developed to represent the sequence of activities, the method can easily be used to do so (IDEF, 2014).

The highest representation of all container terminals is shown in the A0 scheme (see Figure 16). Here the general process of the container handling is visualized with all required controls and mechanisms. The controls mainly refer to data requirements or activation signals, where the mechanisms often show the needed terminal equipment and its operators.

The containerships, trains and trucks enter the container terminal, often loaded with containers. With the help of terminal equipment (visualised below the A0-box), the containers are handled according to the plans that are developed by the Terminal Operating System (TOS). After handling all arrived containers, the containerships, trucks and trains leave the terminal. Because energy is used for all terminal processes, emissions are a result of this energy consumption and can be regarded as output of the handling process.

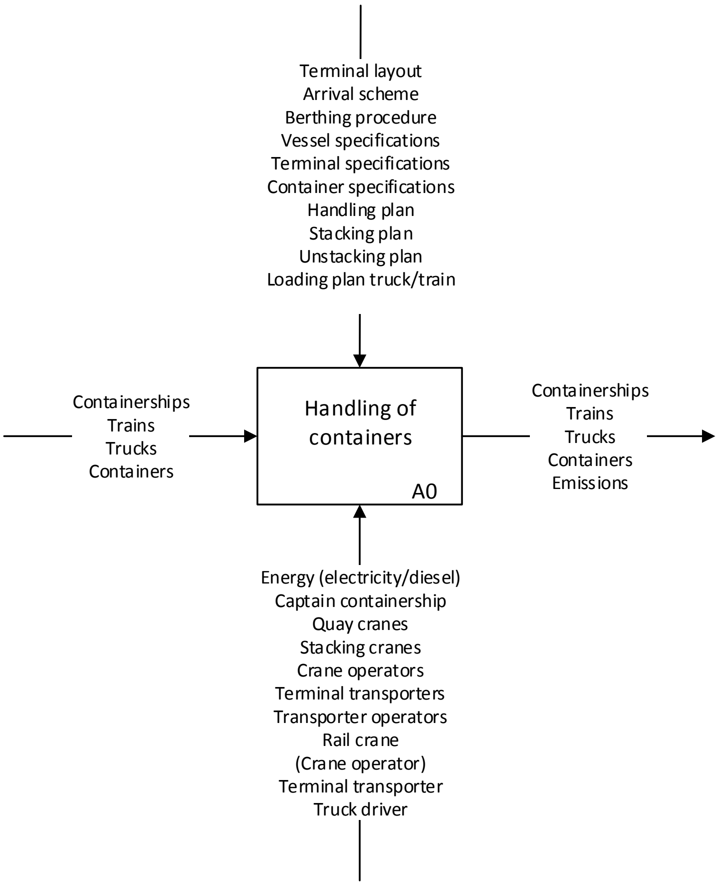

Figure 16: A0 scheme of container terminal

Because of the low level of detail in the A0 overview of Figure 16, the container handling process is decomposed into some deeper levels. This enables a more detailed exploration of all terminal processes and required controls and mechanisms. In these schemes one has to look carefully to the processes where terminal equipment is used as mechanism, because these movements are responsible for the energy consumption of the involved terminal equipment. The IDEF0-schemes of all transporting processes can be found in Appendix A: IDEF0 Process schemes'.

3.1.2 Conceptualisation of consumption model

The IDEF-schemes have identified all terminal processes, concerning the handling of containers. These processes are the ones that are the most interesting regarding the peak shaving of the electricity demand. For all these processes specific types of terminal equipment can be used, diesel-driven or electricity-powered. The processes where terminal equipment is involved are largely the same as the processes that are described in paragraph 2.1.1 to 2.1.6, except for the arrival of containerships. The other processes are the (un)loading of containers between ship and shore, transport of containers between quay side and stacks, the stacking of containers, inter-terminal transport between stacks and trains/trucks and finally the equipment used for (un)loading the trains and trucks.

The processes where terminal equipment is involved are shown in Table 1. On the left side can be seen which IDEF0 schemes correspond to the transport processes. On the right side of the table seven potential sequences of these processes are listed. A major share of all movements is the transport of containers between ship and stacking area, because many containers are stacked first in order to be loaded onto other containerships at a later stage.

Table 1: Possible sequences for transporting containers on terminals

Terminal process and corresponding IDEF0-scheme		Possible movements	Sequence of IDEF-processes
A2-2	Unloading containers at quay side	**Ship to stacking area**	A2-2 > A3 > A4
A2-3	Loading containers at quay side	**Stacking area to ship**	A5 > A3 > A2-3
A3	Transport between quay and stacks	**Restacking**	A5 > A4
A4	Stacking of containers	**Stacking area to train/truck**	A5 > A6 > A7
A5	Unstacking of containers	**Train/truck to stacking area**	A7 > A6
A6	Inter-terminal transport	**Ship to train/truck**	A2-2 > A3 > A6 > A7
A7	(un)loading containers at trucks/trains	**Train/truck to ship**	A7 > A6 > A3 > A2-3

The visualisation of all terminal processes enables an overview of all terminal equipment and corresponding movements. For each of these processes (A2-A7) different types of terminal equipment is used, as can be seen in Table 2. In total four types of terminal equipment can be distinguished: quay cranes, terminal transporters (e.g. reach stackers, straddle carriers, terminal trucks) stacking cranes and rail cranes. The processes where the terminal trucks are partly needed, are the processes where the terminal transport is only needed for the first or last part of the process, where a container is loaded on or unloaded from the transporter.

Table 2: Overview of required terminal equipment per process

Process	Required terminal equipment
A2-2	Quay cranes (& partly terminal transporters)
A2-3	Quay cranes (& partly terminal transporters)
A3	Terminal transporters
A4	Stacking cranes (& partly terminal transporters)
A5	Stacking cranes (& partly terminal transporters)
A6	Terminal transporters
A7	Rail cranes / terminal transporters / stacking cranes

To determine the energy consumption of terminal equipment, it is important to take a closer look at the different movements that are made. In Figure 17 the energy consumption of a quay crane is visualised for a period of eight minutes[5] (MSC Terminal Valencia, 2009). This shows that vertical movements consume significantly more energy than the gantry movements (i.e. horizontal movements of the spreader). The lowering of containers is even generating electricity (negative demand). This shows the need for including the different equipment movements for visualising the dynamic energy demand.

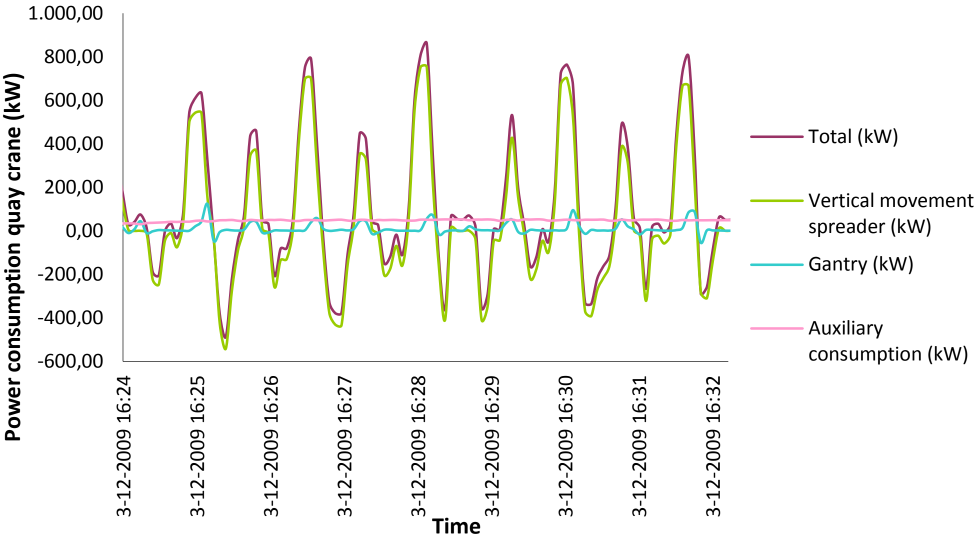

Figure 17: Energy consumption of quay crane over time interval of eight minutes.
Source: (MSC Terminal Valencia, 2009)

For each of the four types of terminal equipment the same method can be used to determine the energy-consuming elements. These elements are derived from the corresponding IDEF-schemes that can be found in the appendices. However, the type of movements differs for some types of terminal equipment (see Table 3). For almost all types a distinction can be made between loaded and unloaded movements, since the transport of loaded containers consumes more energy than unloaded containers. Per type of equipment needs to be determined whether this difference in energy consumption between loaded/unloaded transport is significant.

Table 3: Possible movements of terminal equipment[6]

Terminal equipment	Type of movements
Quay cranes & rail crane	Horizontal movement of spreader (kW/s)
	Hoisting the spreader (kW/s)
	Lowering the spreader (kW/s)
	Movement of quay crane over quay (kW/s)
	Auxiliary / idle state (kW/h)
Terminal transporters	Movement of transporter over terminal (kW/s)
	(Hoisting spreader/container) (kW/s)
	(Lowering spreader/container) (kW/s)
	Auxiliary consumption (kW/h)
Stacking cranes	Movement of crane over terminal (kW/s)
	Horizontal movement of spreader (kW/s)
	Hoisting spreader (kW/s)
	Lowering spreader (kW/s)
	Auxiliary / idle state (kW/h)

The auxiliary energy consumption is not a movement, but is added to Table 3 because of its influence on the energy consumption of (operating) terminal equipment. The auxiliary consumption is a fixed energy demand per hour, needed by inter alia keeping the pressure on the crane and equipment in the cabin and engine room.

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[5] The total power demand that is visualised is the accumulated demand over a time interval of five seconds.

[6] Note that the idle state is considered a 'movement', because the equipment is still consuming energy in this state. (The movements of the crane's arm are assumed to be negligible because they occur only twice per containership.

Together the auxiliary consumption could count up to 140 kW (ABB, 2014). The auxiliary consumption is rather constant over time because the quay cranes are not turned off while in idle or off-shift state. This means that even the idle state is important to include in the consumption model. The terminal transporters are an exception, because they can be switched off completely (ABB, 2014).

By multiplying each of these types of movement with the distance for that movement, the total distance can be calculated, leading to a certain transport time for that movement. When the starting time of the movement is known, the energy consumption can be calculated by adding the energy consumption for that particular movement and the auxiliary energy consumption for that type of equipment. When doing this every second for all movements for all terminal equipment, the energy consumption will be visualised over time (in kW/s). This is shown in Figure 18.

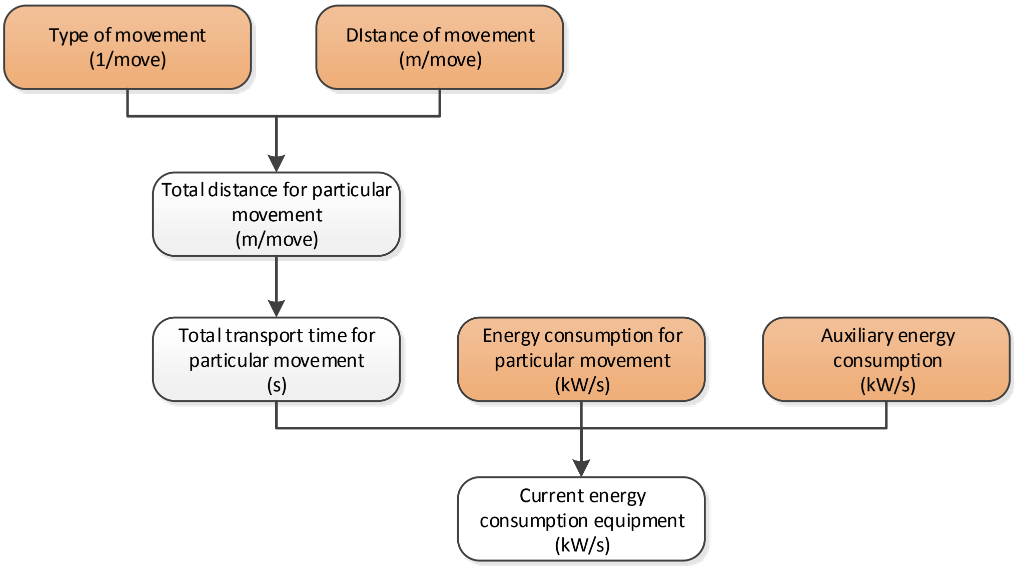

Figure 18: Conceptualisation for determining energy consumption over time interval of movement

Figure 18 shows the energy consumption for a particular movement of a particular type of equipment (since the type of movements differ for each type of equipment, as explained in above) over the time interval for that particular movement. For determining the energy consumption per second (kW/s), some adaptions need to be made to this conceptualisation.

Instead of calculating the distance to be covered, one only needs to know whether the movement is executed or not. In case the movement is executed, the corresponding energy consumption for that movement can be added up to the current energy consumption of the terminal. However, the energy consumption for a particular movement depends on the load of the container (the higher the load, the higher the energy consumption)[7]. The new visualisation is presented in Figure 19 (see next page). In paragraph 3.1.3 this visualisation is converted into the final consumption model.

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[7] Although it is likely to assume, the energy consumption for a particular movement does not depend on the speed of the equipment, since the consumption of terminal equipment is proven stable over different speeds (ABB, 2013).

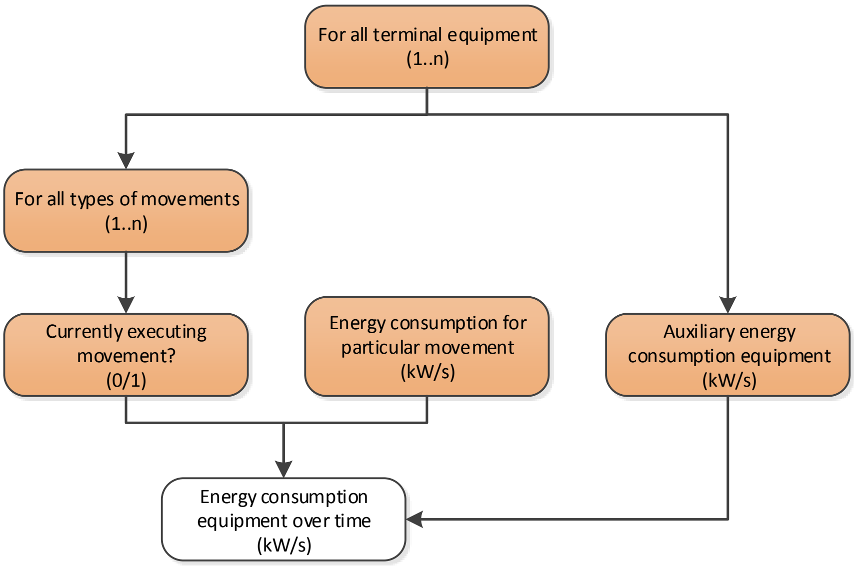

Figure 19: Consumption model for determining the energy consumption per second

3.1.3 Consumption model

The conceptual model of Figure 19 shows the main elements of the energy consumption model for container terminals. For each second in time the movements of terminal equipment need to be determined. The energy consumption of these movements is added to the terminal's energy consumption. The auxiliary energy consumption for every terminal equipment is also added to the current energy consumption. A mathematical representation of the conceptualisation in Figure 19 is given in equation 01.

$$\begin{matrix} Energy\ consumption\ terminal \\ equipment\ per\ second \end{matrix} = \sum_{h=1}^{H=4}\left(\sum_{i=1}^{I=4} m_{ih} * e_{ihl}\right) + a_h \qquad \text{(equation 01)}$$

Where h = type of terminal equipment

H = number of all terminal equipment:
1= quay cranes, 2= (automated) stacking cranes
3= rail cranes, 4= (barge cranes)

i = type of movement

I = number of all movements:
1= movement over terminal, 2= horizontal movement of spreader, 3= hoisting spreader, 4= lowering spreader

m_{ih} = executing particular type of movement for corresponding type of equipment? (binary: 0 if negative, 1 if positive)

e_{ihl} = energy consumption for particular type of movement, particular type of equipment and container load (kW/s)

a_h = auxiliary energy consumption for particular type of terminal equipment

The presented equation enables a relative precise approximation of the energy consumption per second of electrical terminal equipment. All possible movements are predefined for all terminal equipment. Important is the information whether the movements are currently executed. If so, the corresponding energy consumption of that movement is added to the current energy consumption of the container terminal. When doing this over a long time, the dynamics in energy demand will be shown and the peaks will be made visible. Equation 02 (see next page) visualises the mathematical representation when determining the energy consumption per second over a longer time interval. The data needed to apply the consumption model and how to obtain this, is addressed in paragraph 3.2.

$$\begin{array}{c}\mathit{Energy\ consumption\ terminal}\\ \mathit{equipment\ per\ second\ for}\ (T-T_0)\end{array} = \int_{t=0}^{T}\left(\sum_{h=1}^{H=4}\left(\sum_{i=1}^{I=4} m_{ih} * e_{ihl}\right)+a_h\right)dt \qquad \text{(equation 02)}$$

Where $t = 0$ = starting time for measuring energy consumption
T = final time for measuring energy consumption
h = type of terminal equipment
H = number of all terminal equipment:
1= quay cranes, 2= (automated) stacking cranes
3= rail cranes, 4= (barge cranes)
i = type of movement
I = number of all movements:
1= movement over terminal, 2= horizontal movement of spreader, 3= hoisting spreader, 4= lowering spreader
m_{ih} = executing particular type of movement for corresponding type of equipment? (binary: 0 if negative, 1 if positive)
e_{ihl} = energy consumption for particular type of movement, particular type of equipment and container load (kW/s)
a_h = auxiliary energy consumption for particular type of terminal equipment

3.2 Data requirements

3.2.1 Overview of required data

Based on the consumption model of paragraph 3.1 the data requirements can be determined by (and derived from) the variables of the model (referring to the orange coloured blocks in Figure 19). To analyse the consumption of the terminal equipment, first all types of equipment have to be listed together with the number of each type. The operational data should cover the time frame in which movements are executed and the energy consumption for the different movements and the auxiliary state. The terminal layout can be helpful in understanding the terminal's structure. Next to the mentioned data requirements, it is also important to acquire data that can be used to validate the model. In this case the energy consumption per second, preferably originating from the same container terminal. A complete overview of all required data can be found in 'Appendix B: List of required data for consumption model'.

3.2.2 Data search

Different sources can be used to gather the required data. The data can be obtained via collaborating container terminals, earlier research or own (internet-based) research. Below each data source is discussed:

- Data from container terminal

When a particular container terminal is willing to collaborate, the data requirements can be met in the best way because terminals are likely to possess data regarding their equipment, energy specifications and other important details. In that case it is important to check in advance whether the terminals also has the data needed for the validation, because the terminal which delivers the input data for the conceptual model has to be exactly the same as the terminal which provides the data for validation. The usage of data from container terminals might have consequences for the publicity of the outcome, because a collaborating container terminal is likely to demand confidentiality.

- Previous research

Over the last couple of years some research has been executed towards the energy consumption of terminals and terminal equipment. In this way information can be obtained through businesses that operate in this field (e.g. ABB), European initiatives (e.g. GREEN EFFORTS and GREENCRANES) and/or scientific institutes (e.g. TNO). These data sources can be consulted and reviewed in order to find relevant data about energy consumption of terminal equipment and processes.

- Own research

Besides specific terminal-dependent data, energy specifications of different terminal equipment can be found through own - mainly internet - research. This is very general information and data, which increases the need for assumptions and reduces accuracy of the results.

3.3 Development of simulation model

3.3.1 Simulation approach

Modelling is a way to support the problem-solving, especially when experiments cannot be executed easily or are too costly. Over the last years several studies have studied the modelling of (parts of) the processes of container terminals. Where two elements of the research (i.e. representing all energy consuming terminal processes and enabling the testing of alternative designs for terminal processes) can be modelled in various ways (e.g. spreadsheet based programs or simulation tools), the dynamic representation of the energy demand over time point towards the use of a simulation model. This kinds of models can be used to represent the energy consumption over time. This paragraph describes several suitable modelling approaches and their application in academic practice. At the end of the paragraph a choice is made for the most suitable approach.

The existing approaches for modelling container terminals can be categorised as programming-based and mathematics-based, whereby the programming-based studies can be categorised as agent-oriented or object-oriented (Xin, Negenborn, & Lodewijks, 2013).

In this paragraph three modelling approaches will be explained in more detail: the more programming-based Agent-based modelling and Discrete-event simulation and the more mathematical based System Dynamics. These three approaches give a general overview of the approaches that can be applied:

- Agent-based Modelling

  Agent-based modelling is built on four main assumptions: agents are autonomous, interdependent, follow simple rules and are adaptive and backward-looking. The agent-based models are modelled bottom-up and able to adapt their behaviour (e.g. probability or frequency distributions) based on their learning (Macy & Willer, 2002). The agent-based models consist of active and autonomous entities that make their own decisions. The benefits of agent-based modelling are the capturing of emergent behaviours, the natural description of systems and flexibility (Bonabeau, 2002).
- Discrete-event Simulation

  Object-oriented simulations exist of objects that can be described by entities that take over the descriptive attributes and behaviour of the object, but can also have its own attributes and behaviour (Joines & Roberts, 1999). To illustrate this: several gantry cranes (e.g. quay cranes or rail-mounted gantry cranes) adopt the general attributes and behaviour (e.g. lifting function) of the formulated class ‘gantry crane’, but can also have their own unique attributes and behaviour (e.g. speed and lifting capacity). The discrete-event simulation is a well-known simulation program that is based on the object-orientation. In discrete-event simulations the state of the system changes at discrete points in time, called events. The system will remain in its state until an event occurs that may change the systems state (Zeigler, 2003).
- System Dynamics

  Where the earlier mentioned discrete-event and agent-based modelling approaches are based on discrete time-bases, the system dynamics approach has a continuous time-flow. Compared to the other two approaches, the system dynamics approach has the highest abstraction and looks to systems at a macro level (see Figure 20 on next page). A system dynamics model is developed around differential equations and mathematical relations between variables. The system uses feedback loops which describe the system behaviour. Entities in the same stock have the same unit and are threatened equally, which means that there would be no distinction between types of containers within a particular stock (Borshchev & Filippov, 2004).

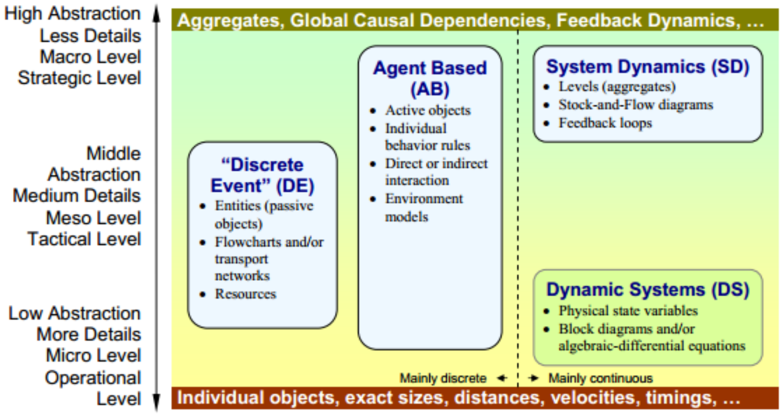

Figure 20: Characteristics of different approaches, ordered by abstraction
Source: (Borshchev & Filippov, 2004)

Application of modelling approaches

In Figure 20 the three described modelling languages are represented. The more object-based discrete event simulation, agent-based simulation and system dynamics approach can be used to model (parts of) container terminal processes. Caballini & Sacone (2014) have modelled the rail operations at container terminals in both a discrete-event approach (Caballini, Pasquale, Sacone, & Siri, 2014) and system dynamics approach (Caballini & Sacone, 2014). Cartenì & De Luca modelled a container terminal environment with a discrete-event approach to simulate the handling activity time duration (Cartenì & De Luca, 2011). Van Asperen et al. (2010) used the discrete event simulation to model and test several container stacking rules, also known as stacking algorithms. Alessandri et al. applied the discrete-event simulation in different studies for modelling the container flows within container terminals, representing the flows as a system of queues (Alessandri, Cervellera, Cuneo, Gaggero, & Soncin, 2008) (Alessandri, Sacone, & Siri, 2007).

A different (mathematics-based) approach is developed by Xin et al. (2013). In order to include both the discrete-event dynamics and continuous-time dynamics of terminal equipment they combined a hybrid system and model predictive control (MPC). The hybrid system is able to combine the discrete-event en continuous time dynamics and the MPC is able to deal with many variables with constraints and multiple objectives.

Choice of modelling approach

The choice for a modelling approach very much depends on the feasibility to represent the dynamic energy consumption of terminal processes, while visualising the execution of the process events at container terminal and enabling the modeller to adjust the model easily for testing different scenarios. The three discussed approaches have been compared on several characteristics (see Table 4).

The agent-based approach does not satisfy this purpose because the objects are modelled as autonomous agents which follow the predefined rules to behave themselves in the system and because the agent-based approach does not facilitate an event-based modelling of the processes. The system dynamics approach cannot fulfil the stated requirements because the objects are represented in flows and special specifications cannot be assigned to separate entities. Despite the noncompliance of the agent-based and system dynamics approaches, the discrete-event approach is a suitable approach to fulfil the requirements due to its event-based character and ability to appoint attributes per entity.

The conclusion is therefore to use the discrete-event approaches for constructing the simulation model. For this purpose the Simio simulation software package of Simio LLC is used. Nevertheless one should keep in mind that different approaches and software packages have been used to model container terminals, each having their own advantages and disadvantages.

Table 4: Comparison of modelling approaches

Characteristics	Modelling approaches		
	Agent-based	**Discrete-event**	**System dynamics**
Type of objects	Active	Passive	Flows
Behaviour	Autonomous	Predefined	Predefined
Ability to change attributes per entity	Yes	Yes	No
Distinctive benefit	Shows emergent behaviour	Event-based	Shows behaviour of large interdependent systems

3.3.2 MSC Terminal Valencia

The terminal that is used as a case study for applying the energy consumption model is the MSC Terminal in Valencia (MSCTV). The MSCTV has a surface of 35 ha. and quay length of 774m. Eight super post panama quay cranes handle an annual throughput of 1.6 million TEU. The MSCTV has a dated terminal configuration and its terminal operations are largely dependent on terminal equipment which are diesel-powered (e.g. terminal trucks for on-terminal transport, rubber-tired gantry cranes for the stacking of containers and reach stackers for (un)loading trains and trucks). The only electrical powered equipment are the eight Super Post Panamax PORTAINER® quay cranes from Paceco (see Figure 21). These cranes have an outreach up to 65 meter and the spreader is able to lift a maximum of 65 tonnes gross weight over 41 meter (Paceco España, 2010).

Figure 21: Super post panamax quay cranes at MSC Terminal in Valencia.
Source: MSCTV (2010)

All electrical powered processes (i.e. the eight quay cranes, reefers, terminal lighting and other processes like buildings and workshops) consume over 12 million kWh (MSC, 2012). In Figure 22 is shown how this consumption is distributed over the mentioned processes. The quay crane operations are responsible for 50% of the energy consumption of the MSCTV and show a highly volatile demand. This is the reason for demarcating the simulation model around the operations of the quay cranes.

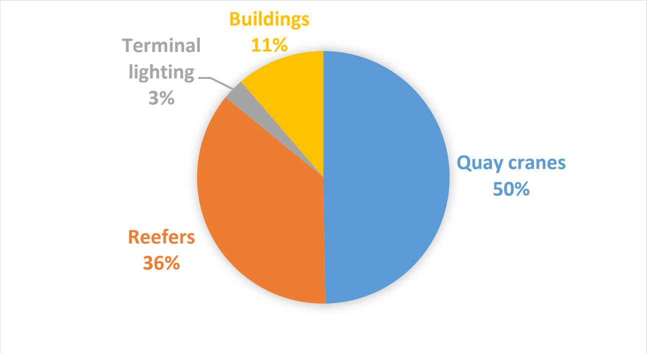

Figure 22: Distribution of energy consumption (kWh) of MSCTV (2012)

3.3.3 Model specifications

Now the simulation approach and case-study container terminal to apply the consumption model have been chosen, the simulation model can be constructed. In paragraph 3.1.2 the data requirements for the consumption model are discussed (see also 'Appendix B: List of required data for consumption model'). In order to apply the consumption model in a simulation environment for a real container terminal, the following data have to be available:

- terminal layout specifications (i.e. number of quay cranes);
- arrival scheme containerships;
- number of containers to be handled;
- container load specifications;
- position of containers;
- energy consumption specifications.

The terminal lay-out specifications are needed to understand the setup of the terminal's quay cranes and the number of operating quay cranes. Based on the arrival scheme and number of handled containers per containership the different movements can be simulated. Derived from the containers' location on the ship and the speed of the quay crane, the duration for each movement of the quay crane can be determined.

The data for constructing the simulation model is provided by ABB, a professional company active in the field of electrical engineering and automatisation. The obtained data fulfils the above mentioned requirements. Divided over the different type of movements and different container loads (varying from 0% for empty containers to 100% for full containers, with intervals of 10%) the energy consumption and duration are known. However, there is a difference compared to the four types of movements for quay cranes presented in paragraph 3.1.

ABB makes a distinction between the hoisting and lowering of the quay crane above the containership and above the quay. This means that the total number of movements increases from four to six. Next to this, ABB subdivided the six movements into 2-3 sub-movements to enable a more detailed visualisation of the energy demand of the quay cranes. An example is the movement of the spreader from quay to ship. The first part of the movement consumes energy because the spreader needs to accelerate. However, the second (and last) part of the movement generates energy because the spreader is slowed down. In this way the peaks can be visualised more realistically, as is shown in Figure 23. As can be seen, the blue line has higher peaks and lower falls than the orange line (using an average energy consumption per movement), which shows the extra detail that is obtained when using sub-movements for visualising the energy demand.

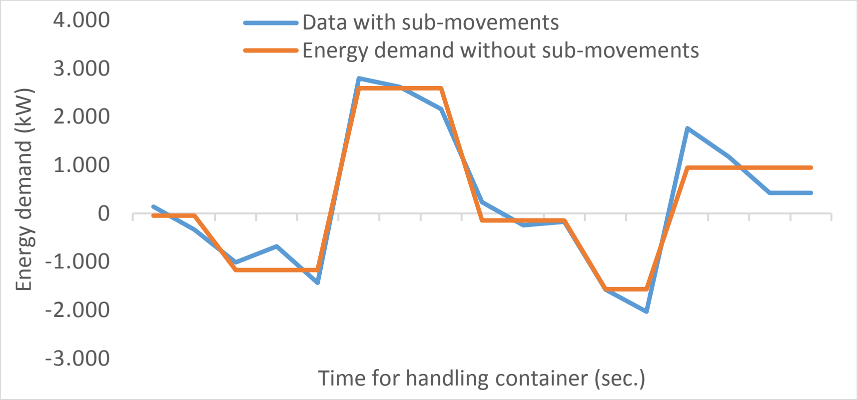

Figure 23: Energy demand for handling a container with and without sub-movements (ABB, 2014)

The simulation model is constructed to measure the peak energy demand (in kW/s) as well as the handling time for the number of containers that are included in the simulation run. This enables the research of the trade-off between the reduction of the energy demand and the corresponding consequences for the handling time (see chapter 1). This is tested for different rules of operation, which will be introduced in chapter 4 in more detail. Figure 24 gives an overview of all inputs and outputs of the simulation model, as well as the rules of operation that are tested. The rules of operation will be explained in more detail in chapter 4.

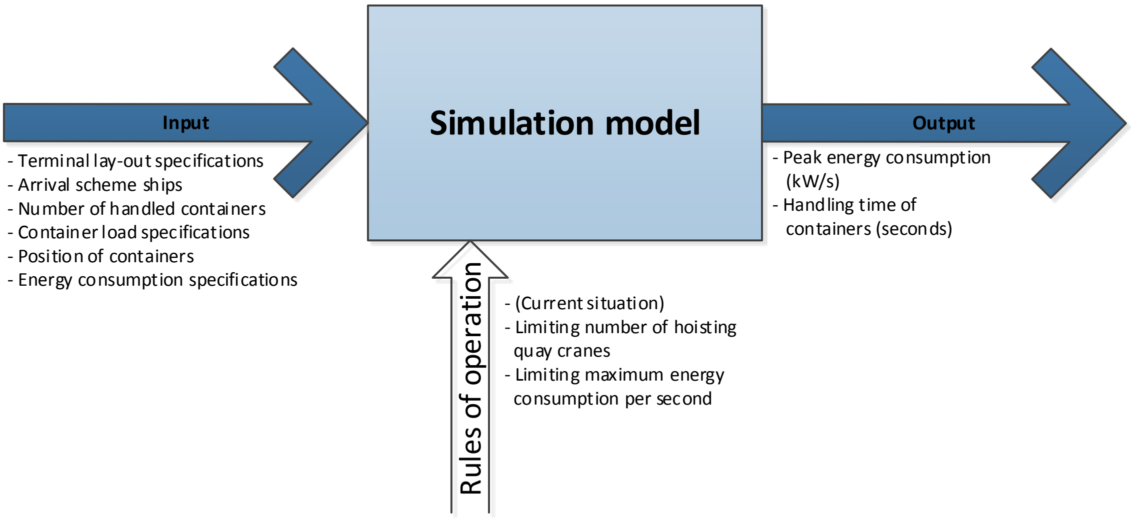

Figure 24: Overview of inputs and outputs simulation model

3.3.4 Scope and time span

The scope of the simulation model deals with the operations of the quay cranes, since this is the only electricity consuming terminal process at MSCTV that experiences a strong volatile demand change over time. For this purpose the quay crane handling processes are decomposed to give a more detailed understanding of the operations. In 'Appendix C: IDEF0 process schemes for (un)loading containers' the two decompositions for the processes of unloading and loading containers at the quay side are presented. Based on this extensive process description (where all possible movement of the quay cranes have been included) and the developed energy consumption model a simulation model can be developed.

The rules of operation are compared with each other based on a week of operations at the MSCTV (1-7 December 2012). In this time period 19 containerships arrived, ranging from 303 to 3,805 TEU per containership, with an average of 1,058 TEU per containership. In total, the container terminal handled 20,114 TEU during that week. Because the simulation model assumes a container handling with 40ft containers only (see paragraph 3.3.5), the number of containers that arrive in the simulation model is set to 10,057 containers[8]. The detailed arrival scheme can be found in 'Appendix D: Arrival scheme containerships'.

The run length of the simulation period is one week, which is 168 hours. The longest cycle time within the simulation model is the handling of the largest containership. With an average handling time of 78.0 seconds per container (ABB, 2014) and eight available quay cranes, the handling of the 3,805 containers would take approximately 10 hours[9]. A rule of thumb is that the runtime of the model should be at least three times the longest cycle time (Kelton, 2000). This precondition is satisfied in the simulation model, since the run time is sixteen times the longest cycle time. No warm-up period is used, because the arrival times of containerships are based on a data table (see 'Appendix D: Arrival scheme containerships'). The number of replications is discussed in paragraph 3.5.1.

3.3.5 Model assumptions

For constructing the simulation model some assumptions have to be made due to the lack of precise data or to simplify (sub) processes of some complex terminal operations. The assumptions are divided over three categories: significant impact, low impact, negligible impact and unknown. Especially the significant assumptions and assumption with an unknown effect are important because of their potential influence on the results of the simulation model.

Significant

- The spreader of a quay crane is able to lift one 40ft. container or two 20ft. containers per move. The spreader always transports 2 TEU per move (i.e. two 20ft. containers or 40 ft. container).
  <u>Effect</u>: in reality not all 20 ft. containers are moved in pairs, which means that the average of 2 TEU/move is assumed too high. The number of 20ft. containers is around 50% of all handled containers

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[8] $\frac{21{,}114\ \text{TEU}}{2\ \text{TEU/container}} = 10{,}057\ \text{containers}$

[9] $\frac{3{,}805\ containers * 78\ sec./container}{8\ \text{quay cranes}} = 10.3\ \text{hours}$

(MSC Terminal Valencia, 2012). If only half of the 20ft. containers are transported in pairs, the average is around 1.7 TEU/move, which increases the number of moves with 14%. For 25% of the simulated movements the energy consumption will be less than modelled, because the movement is executed with only one 20ft. container instead of two. The exact influence on the energy demand is unknown because the data makes no distinction between moving a 20ft. container and a 40ft. container, but is considered to be significant. In general can be stated that if the number of moves increases and the container weight decreases, the peak demand will be lower.

Low

- The data uses average energy consumption specifications for containers, dependent on their load percentage (100% is full load, 0% is an empty container). The location of the container on the ship is not included in the provided data, which means that for all container the same location is assumed.

  Effect: the effect on the peak in energy demand is not significant, as shown in the sensitivity analysis (see paragraph 3.4.2). The change in peak demand was proven to be only 0.75%.
- The movements of quay cranes on their track on the land side of the terminal is neglected because there is no data known about the energy consumption for this type of movement.

  Effect: this might affect the outcome in the way that the corresponding energy consumption is not included in the total energy demand, however the energy demand of this type of movement is considered low (ABB, 2014).

Negligible

- No distinction is made between the incoming containers and outgoing containers, because the available data does not provide for this.

  Effect: the consequence of this assumption is negligible, because the same movements are made for incoming and outgoing containers. A difference is that some energy specifications will be swapped, e.g. the highest peak for incoming containers (which is the hoisting above the ship) will be shifted towards hoisting the container above the quay (in case of outgoing containers).
- There are always trucks available at the quay cranes for containers to be loaded from quay crane onto the terminal truck. The consequence is that the quay crane processes are not delayed by terminal trucks that are assigned to pick up containers at a particular quay crane and which do not arrive in time.

  Effect: this assumption allows the quay crane to continue its movement directly from horizontal ship to shore process into the lowering at quay side process, without holding the container to wait for the arriving terminal trucks. The holding of a container would not increase the energy demand (the energy consumption for holding a container is not higher than for moving a container). The only effect would be that a quay crane could not continue its operations directly. Because the model is stochastic, it is expected that this assumption does not affect the energy peak demand.

Unknown

- In the new rules of operation, where either the energy consumption or number of lifting quay cranes is limited, some containers are queued during their movement from ship to shore (or vice versa), which means that containers can temporarily be stopped moving between different movements. It is assumed that quay cranes do not consume energy during these stops.

  Effect: in reality some energy will be consumed for holding a container in its place. Unfortunately it is not known how much influence this assumption has on the model.

3.4 Description of simulation model

After the conceptual model for the simulation has been developed according to the presented characteristics and assumptions (see paragraph 3.3), the model is constructed. In this paragraph the model is described in general, followed by the model verification (including sensitivity analysis) and validation (Sargent, 2013).

3.4.1 Model description

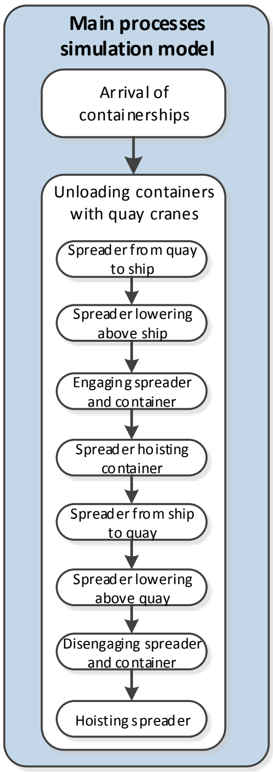

Figure 25: Main processes of simulation model

When a containership arrives at the container terminal, the ship berths and the terminal's quay cranes start the handling of containers immediately. The quay cranes take the containers through six main processes (i.e. movements, see Figure 25):

- Moving spreader horizontally from quay (idle position) to ship;
- Lowering spreader above ship to get a container;
- Lifting spreader and container from ship;
- Moving spreader and container horizontally from ship to quay side;
- Lowering spreader and container to terminal truck on quay side;
- Lifting spreader from quay (to idle position).

As discussed in paragraph 3.3, each of the six general movements is divided into two or three sub-movements to give a more detailed outcome of the energy demand. For each movement a container has its own process times and corresponding energy consumption specifications.

After the quay crane processed the container through all movements, the container is picked up by a terminal truck, bringing the container to the stacking area. Because the terminal trucks are diesel-powered, this process does not influence the peak demand in electricity.

The model is able to generate the following relevant output:

- energy consumption per second (kW/s);
- peak demand during run time, based on intervals of 0.1 second (kW);
- total handling time for all handled containers (seconds);
- number of active quay cranes;
- number of lifting quay cranes;
- number of containers that were ceased and their average ceasing time (due to limitations imposed by the rules of operation).

The price of the peak demand is calculated based on the highest observed peak demand.

In Figure 26 and Figure 27 two screen view of the simulation model are shown. Here eight quay cranes are transporting the containers (red triangles) through the different (sub-)movements (grey process blocks). Several information blocks with numerical information show the state of different measurement variables (mainly regarding the above described outputs of the simulation model).

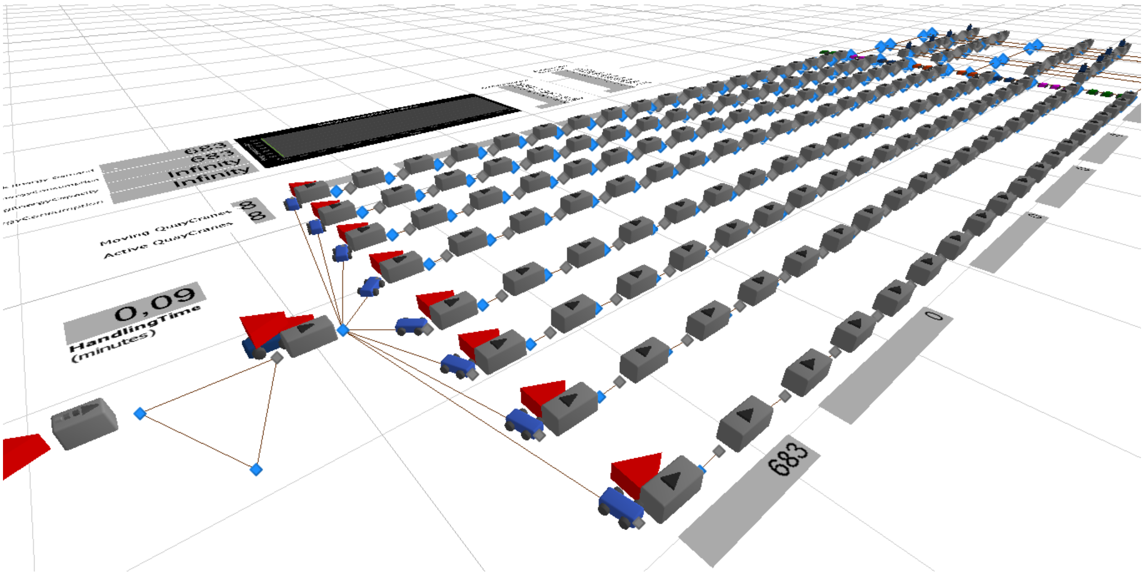

Figure 26: 3D screenshot of simulation model, running for an 8-crane terminal.

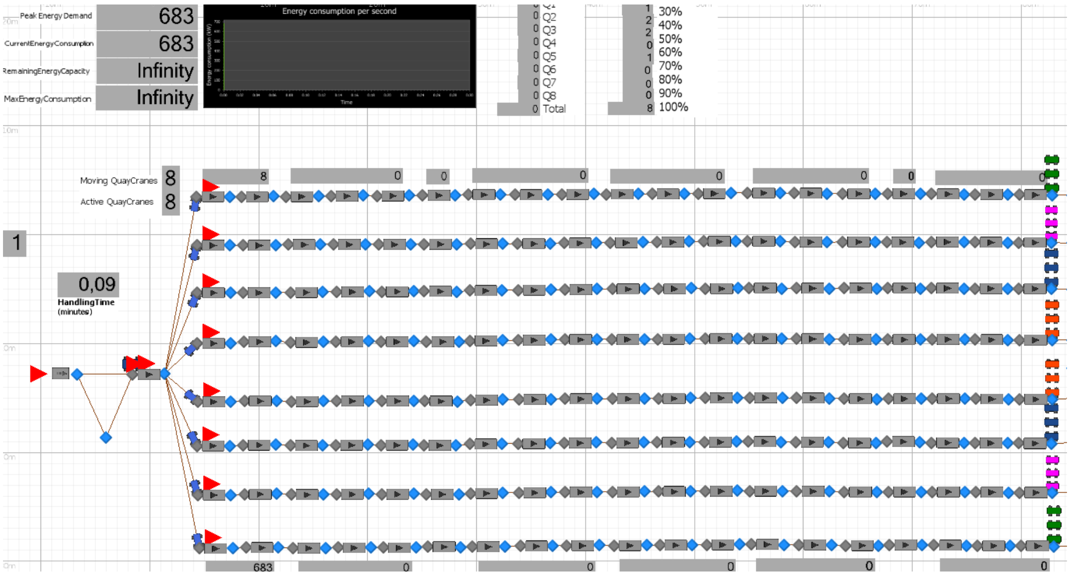

Figure 27: 2D-screenshot of simulation model, running for an 8-crane terminal.

3.4.2 Model verification and sensitivity

To test whether the simulation model is working correctly, a verification is executed. The verification tests for errors and unwanted behaviour. It cannot be proven that the model is working 100% right. However, extensive testing can give a good view whether the model works in a correct way (Kelton, Smith, & Sturrock, 2011). The tests – and corresponding hypotheses – that are executed are the following:

- containership with only one container arriving (to test if not multiple quay cranes are assigned to one container, hypothesis: only one quay crane is assigned to handle the container);
- containerships with 100 containers arrive, while only one quay crane is available (to test if not more than one quay crane is used, hypothesis: one quay crane is handling all 100 containers). This test is repeated for same number of containers with resp. 2-7 quay cranes available;
- a couple of containerships arrive at the same time (to test whether the container handling is not disturbed and the quay cranes start operating both containerships instead of only one, hypothesis: the quay cranes handle the containers as if the originated of one containership);
- a containership with a fictive number of 25,000 containers is arriving (to test whether the model can cope with such a big number of containers, hypothesis: the model is working correctly although it might take some time to 'load' the containers in the simulation);
- for all container types (dependent on the container load) the process times of all movements is set to 0 (to test whether the containers are handled immediately, hypothesis: all containers are handled without consuming time, the energy consumption stays the same);
- for all container types (dependent on the container load) the process times of all movements is set to one hour (to test whether the quay cranes are handling the same containers for hours instead of handling multiple containers simultaneously, hypothesis: the quay cranes will not handle more than one container at the same time).

After executing these tests, all hypotheses are proven correct. In this way the model is working properly.

Next to the (extreme) value testing, it is also interesting to test whether some numerical inputs are also shown while running the simulation. Because the energy use and duration for the movements is predefined in hard values (meaning that a container with a container load of 20% always consumes the same energy and has always the same handling time), the container load distribution is the only distribution that can be verified. After executing the verification test, the difference between the predefined percentages and the results of the test are not larger than 0.6%, without influencing the peak demand. On this point the model can be considered working properly. The detailed results of this verification can be seen in 'Appendix E: Results verification and sensitivity analysis'.

Next to this test, the sensitivity of the process times on the energy demand is tested. This is done because the process times are – as indicated before – hard values (i.e. without distributions). However, one container may be located near the quay side, where another container is located to the water side of the ship. This might lead to different process time when handling the container in reality. After applying a sensitivity to the process times, the result is that the distribution would have a difference of only 0.75% on the peak demand, meaning a cost difference of only €3,700 per year. The conclusion is that the model is sensitive on this point, but the sensitivity is not influencing the model outcome significantly. A more detailed explanation (including graphs) of the numerical verification and sensitivity analysis, is presented in 'Appendix E: Results verification and sensitivity analysis'.

3.5 Model validation

3.5.1 Design of experiments

Before the results of the base scenario (i.e. current situation without implemented rules of operation) can be described and the model can be validated, a test run has to be done to determine the desired number of replications that need to be executed to get reliable results out of the experiments for the developed rules of operation. The test run is developed based on the theory of Van Soest (1992). Van Soest states that the desired number of replications is dependent on the number of replications that is executed for the test run, the highest observed value of performance variable and the corresponding half width of that variable. The formula is visualised in equation 03.

$$desired\ nr.of\ replications = repl.test\ run * \frac{half\ width\ confidence\ interval}{\frac{highest\ value\ * 0.05}{2}} \qquad \text{(equation 03)}$$

In the test run with 10 replications, the highest observed value is 18,057 kW[10]. The half width of the peak demand is 364.45, which gives a desired number of replications of 8, as can be seen in equation 04 below.

$$desired\ nr.of\ replications = 10 * \frac{364.45}{\frac{18{,}057\ * 0.05}{2}} = 8.1 \qquad \text{(equation 04)}$$

The result of this calculation is that the experiments that are executed to test the rules of operations (see chapter 4) need to be executed with eight replications per scenario.

The replication settings of Simio are such that replications are independent of each other. Each replication uses a different set of random generated numbers (Kelton, Smith, & Sturrock, 2011). However, the same initial preconditions are used to ensure the comparability of replications with each other.

3.5.2 Results base scenario

The base scenario of the simulation model is executed with the standard specifications of the container terminal. This means that all eight quay cranes are handling containers, without any restrictions towards the number of simultaneously lifting quay cranes or maximum energy demand per second. The base scenario is run with ten replications (more than the minimum desired eight replications, as calculated in the last sub-paragraph). As discussed earlier, the time span is one week. During this week 19 containerships arrive with a total of 10,057 containers (40ft. containers).

The average maximum energy demand of all replications is 19,177kW, with a minimum of 18,063kW and a maximum of 20,004kW. The corresponding half width is 364.4kW. The handling time of all containers is 1,857 minutes, which is 31.0 hours.

Figure 28 gives an overview of the energy demand frequency per 0.1 second. Here the idle times are neglected. As can be seen, a maximum energy demand of 18,000+ kW is only consumed during a very small time period. An energy demand higher than 9,000kW is observed in only 1.1% of the time. This endorses the hypothesis that the highest peak demand can be reduced without influencing the operations too much.

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[10] The auxiliary energy consumption of quay cranes is not included in the output of the energy consumption. This means that a peak demand of 18,057kW in the simulation model corresponds to a real peak demand of 19,177kW.

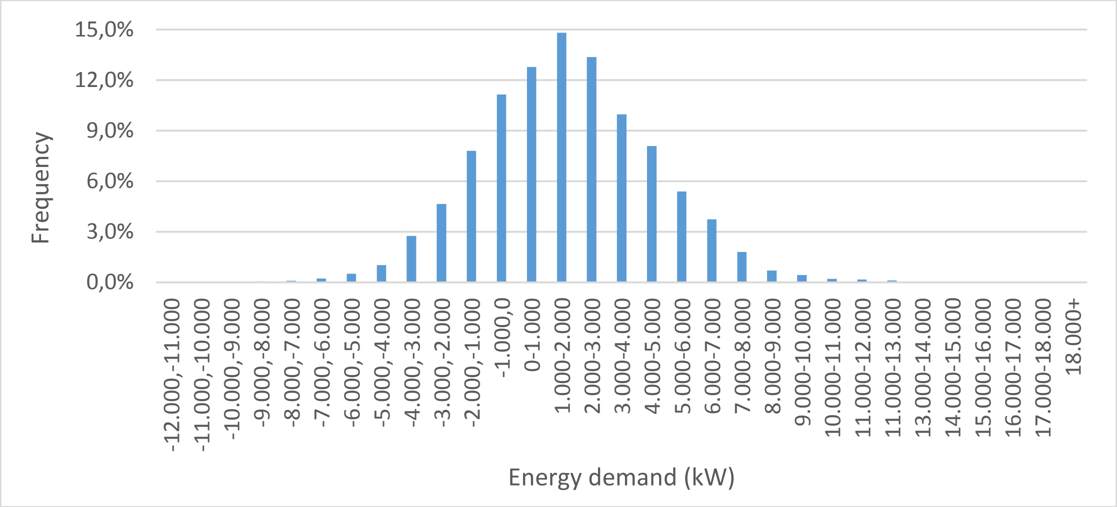

Figure 28: Frequency graph for energy demand (measured per 0.1s)

3.5.3 Validation simulation model

The model validation is executed to check whether the energy consumption of containers in the simulation is corresponding with real data. This is done for several criteria:

Energy demand

Each container load (0% - 100%) has its own pre-defined energy specifications (kW/s). Multiplied by the operation times per sub-movement, the total energy consumption for a container can be determined. The theoretical energy consumption (based on the data) is compared with the results of the simulation model. The result (see Table 5) is that the maximum difference in energy consumption is 0.9%. For most container loads the difference is not larger than 0.2%.

Table 5: Validation for energy demand of simulation model

Container load	Energy demand real data (kWh)	Energy demand model (kWh)	Difference
0%	2.12	2.12	0.00 (0.00%)
20%	5.01	5.00	-0.01 (-0.20%)
30%	5.73	5.75	+0.02 (0.35%)
40%	6.26	6.25	-0.01 (-0.16%)
50%	5.05	5.05	0.00 (0.00%)
60%	4.44	4.48	+0.04 (+0.90%)
70%	4.76	4.78	+0.02 (+0.42%)
80%	4.87	4.86	-0.01 (-0.21%)
90%	4.86	4.86	0.00 (0.00%)
100%	5.20	5.20	0.00 (0.00%)

Because the different container loads are not appearing in the same proportion, the difference is multiplied with their appearance distribution (container mix). The results is a weighted difference of 0.26% (see Table 6 on next page), which might be considered not significant to the energy consumption results. The influence on the energy peak is however difficult to calculate, because that depends on the current container mix, which is changing continuously in the simulation model.

Table 6: Weighted difference for difference in energy demand

Container load	Container mix	Difference	Weighted difference
0%	12.5%	0.00%	0.00%
20%	32.0%	0.20%	0.06%
30%	11.1%	0.35%	0.04%
40%	11.4%	0.16%	0.02%
50%	13.6%	0.00%	0.00%
60%	13.6%	0.90%	0.12%
70%	3.3%	0.42%	0.01%
80%	1.6%	0.21%	0.00%
90%	0.6%	0.00%	0.00%
100%	0.3%	0.00%	0.00%
		Total weighted average	**0.26%**

Peak demand

When comparing the peak demand of the simulation (base scenario with eight lifting quay cranes and no restriction towards the maximum energy demand per second), the peak demand lies around 20,000kW. This is consistent with data that of a terminal with eight quay cranes (ABB, 2014), which validates the outcome of the simulation model on this aspect.

Handling time

The total run time for the base scenario is 171.0 hours (one week plus three hours extra run time). The quay cranes are operating 18.0% of the time (half width 0.5%), which is 30.8 hours. In this time frame 10,057 containers are handled. Based on the fact that eight quay cranes are operating, resulting in a handling time of 88.1 seconds/container.

The theoretical (weighted) handling time of a container (based on the appearance of each container load) is 91.4 seconds/container, a difference of 3.3 seconds (3.6%). This difference could be explained by random distribution of process times for engaging the container in the simulation model, while the theoretical handling time makes use of standard process times instead of a distribution.

3.6 Conclusion

When developing a consumption model for the dynamic representation of the electrical power consumption at a container terminal, existing models do not satisfy the requirements for this visualisation. The consumption model that is presented in this chapter makes a distinction between the different movements of terminal equipment, since the energy consumption differs for each type of movement. Vertical movements (hoisting and lowering the spreader and container) consume much more energy than horizontal gantry movements.

The consumption model showed that the electrical energy consumption of terminal equipment depends on the different movements for transporting one or more containers (e.g. driving, lifting, lowering and gantry) and an auxiliary consumption. The consumption of terminal equipment (kW) can be calculated when having the following information:

- Number of terminal equipment;
- Overview of different movements per type of equipment;
- Operational information (to determine at which moment a movement is executed);
- Energy consumption per movement (kW/s);
- Auxiliary energy consumption (kW/s).

The third sub-question – questioning whether it is feasible to develop a consumption model that takes into account all relevant aspects of the electrical energy consumption of a container terminal and which shows the consumption over time – can therefore be answered positive (see Figure 19 and equations 01 and 02).

For applying the consumption mode, a reliable data provider is needed, since the list of required data is rather extensive. Especially because the required data is quite detailed at the point of the energy consumption of the different movements. This might be valuable information for container terminals, which they are not willing to share. The more precise data that is obtained, the better the prediction of the consumption model. However, when data is not available, assumptions need to be made in order to make an approximation of the energy consumption. A disadvantage is that assumptions might harm the preciseness of the model results.

The presented model is not only useful for estimating the energy consumption for container terminals, it can also be used in other industries where different electrical equipment is operating in different movements, e.g. cranes and robots at construction sites or within factories. The same principle of dividing the equipment's operations into different movements can be applied easily and can help other industries to understand their energy consumption (and see the peak demand and corresponding costs).

When applying the consumption model in a case-study for an existing container terminal, the best way to model the container terminal operations and more specific the quay crane operations is using a discrete-event simulation. The main reason for this is the event-based character of the simulation method. The assumptions that were made to develop the simulation model influence the outcome of the simulation, but not for all assumptions the exact influence is known. This means that the results of the simulation model should be interpreted with this sensitivity in mind. The observed peak demand lies around the 20,000kW for a container terminal with eight quay cranes. Chapter 4 presents the rules of operation that are developed to smoothen the energy demand in order to lower the peak demand of 20,000kW. This peak alone costs a container terminal over €500,000 per year, based on the price that grid operators charge per kW peak demand.

The arrival of five new quay cranes for ECT at the Port of Rotterdam, transported by the Zhen Hua 26
Photo: gCaptain.com (20 January 2014)

4. Evaluation of peak shaving opportunities

After the energy consumption model and simulation model have been developed (see chapter 3), the question that is addressed in this chapter is how the peak demand of a container terminal is influenced by the earlier presented rules of operation (see chapter 2.4) to investigate the opportunities for peak shaving the electricity demand (sub-questions 6 and 7). The rules of operation are applied for two types of container terminals (6 or 8 quay cranes), while the effect on both the peak demand and the handling time of containerships are monitored. Especially the trade-off between the peak demand and handling time is very interesting, since it is expected that a lower peak demand affects the handling time (see chapter 1 for more information about this trade-off).

First, the results of the executed tests are discussed per rule of operation (paragraph 4.1 and 4.2). In paragraph 4.3 all results are discussed integrally and the optimal solutions are presented. Paragraph 4.4 discusses the implications of these results for container terminals and their customers, the container carriers. The chapter is concluded in paragraph 4.5.

4.1 Limiting simultaneously lifting quay cranes

As described in paragraph 2.4, a quay crane needs to lift its spreader twice during the handling of a container on the terminal. When a ship arrives the first lifting movement is when the container is hoisted above the ship. The second lifting movement is when the spreader is hoisted above the quay, directly after the container is placed on a terminal transporter (or on the terminal itself, dependent on the terminal). If the number of simultaneously lifting quay cranes is restricted, some quay cranes need to wait until another quay crane has finished its lifting before it can continue its activity.

To analyse the impact of this rule of operation, several scenarios are tested for the two different types of container terminals (see Table 7 below).

Table 7: Scenarios for limiting the lifting of quay cranes

	Number of simultaneous lifting quay cranes	
	6 quay cranes	8 quay cranes
Base scenario	6	8
Limiting scenarios	5, 4, 3, 2, 1	7, 6, 5, 4, 3, 2, 1
Total number of scenarios	*6*	*8*

The outcomes of these scenarios are presented in Table 8 and Table 9. What strikes is that the handling time of the containers is not increasing drastically when the number of lifting quay cranes is limited from 8 to 4 or from 6 to 3, while the peak related costs can be reduced by almost 40%. The handling time is increasing 0.37% - 0.44%, which means an increase of 13 - 16 seconds per handling hour. On an annual base this would imply an extra handling time of only 9 - 11 hours, saving the container terminal €155,000 (6-crane terminal) to €195,000 (8-crane terminal) when the number of simultaneously lifting quay cranes is reduced to half of the operational quay cranes.

The half width of the peak demand is 467.6kW (8-crane terminal) and 312.3kW (6-crane terminal) which means that the peak demand is quite reliable. A more detailed table with results can be found in 'Appendix F: Results simulation model'.

Table 8: Effect of limiting the number of lifting quay cranes for 8-crane terminal

Number of simultaneously lifting quay cranes	Peak demand (kW/s)	Handling time (hours/year)	Cost peak demand (€/year)
(base scenario) 8	**19,230**	**2460.0**	**€518,000**
7	-7.3%	+0.08%	-€38,000
6	-18.9%	+0.18%	-€98,000
5	-29.0%	+0.27%	-€150,000
4	-37.7%	+0.37%	-€195,000
3	-52.0%	+1.17%	-€269,000
2	-65.2%	+5.87%	-€338,000
1	-78.7%	+85.43%	-€407,000

Table 9: Effect of limiting the number of lifting quay cranes for 6-crane terminal

Number of simultaneously lifting quay cranes	Peak demand (kW/s)	Handling time (hours/year)	Cost peak demand (€/year)
(base scenario) 6	**14,940**	**3,277.4**	**€403,000**
5	-11.1%	+0.03%	-€45,000
4	-25.5%	+0.07%	-€103,000
3	-38.5%	+0.44%	-€155,000
2	-56.1%	+2.19%	-€226,000
1	-74.5%	+39.3%	-€300,000

When taking a closer look to the results, Figure 29 below shows the relation between the peak demand and handling time for the 8-crane terminal. The observed peak demand is decreasing almost linear, where the handling time is quite steady until the moment when the number of simultaneously lifting quay cranes is restricted too much. The turning point is when the number is reduced to less than 2 - 3 lifting quay cranes. This means that the number of simultaneously lifting quay cranes can be reduced to four quay cranes without infecting the handling time that much (maximum 0.37%).

The steep increase in handling time, that is observed when the number of lifting quay cranes is restricted to less than three quay cranes, can be explained by the fact that if the number of simultaneous lifting quay cranes is restricted too much, other containers are delayed in such a way that the operations are infected more (see also Figure 31 on page 50, where the percentage of delayed containers is visualised). The fact that the handling time is not affected that much when reducing the number of simultaneously lifting quay cranes by 50% can be explained by the fact that containers are spread over the whole ship-to-shore process, which means that not all quay cranes are executing a lifting movement at the same time. When restricting the number of lifting quay cranes, the chance that containers will be in the same lifting process becomes higher, which leads to higher handling times.

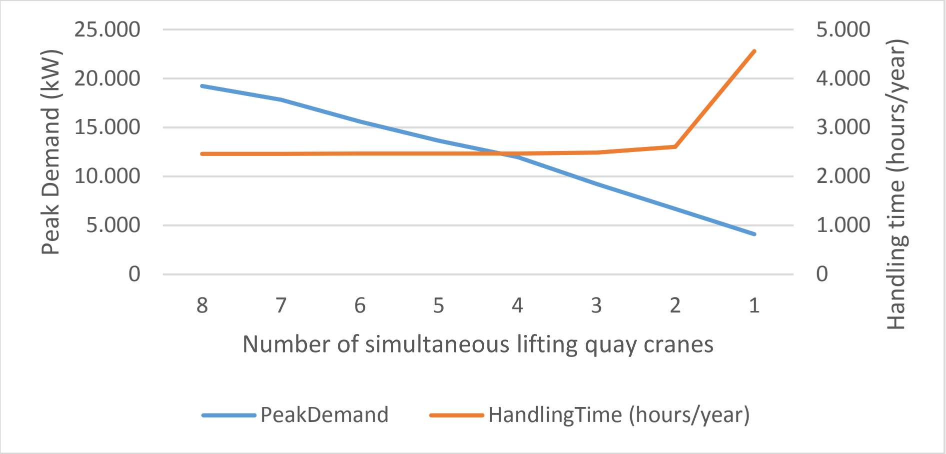

Figure 29: Relation between peak demand and handling time (for 8-crane terminal)

As the peak demand reduces by limiting the number of simultaneously lifting quay cranes, the potential cost reduction per year increases. The correlation between these variables is -1.00, which means that the total cost saving is always increasing when the number lifting cranes is limited (see Figure 30).

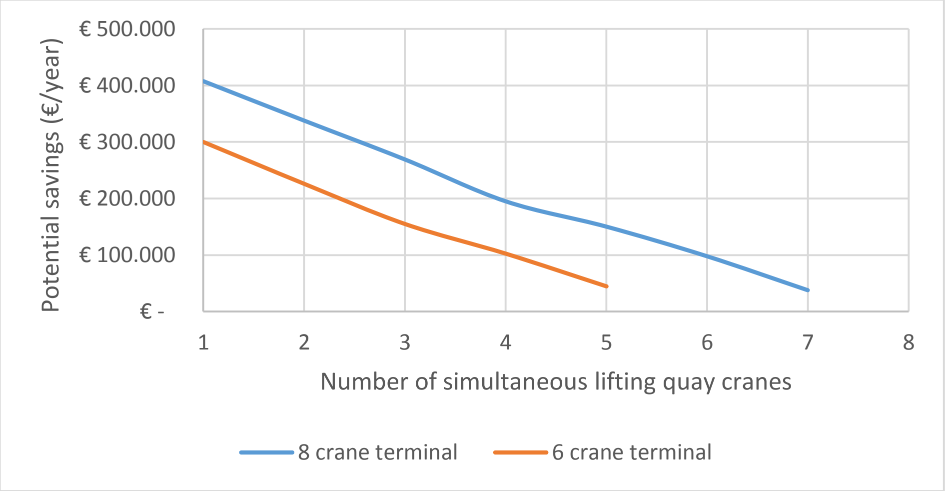

Figure 30: Potential savings per year for reducing number of lifting quay cranes

The restriction on simultaneously lifting quay cranes has effect on the handling time for containers (see Table 8, Table 9 and Figure 29). This means that the more the number of lifting cranes is restricted, the more containers are delayed in their handling process. However, Figure 31 (see next page) shows that the number of containers that is delayed, is only increasing drastically when the number of lifting quay cranes is reduced by more than 50% to 3 or less (8-crane terminal) or 2 or less (6-crane terminal) quay cranes. The average waiting time for containers that are delayed is quite stable, but is also increasing when the number of lifting cranes is restricted too much (see Figure 32 on next page). In general can be stated that the higher the number of delayed containers, the higher the average waiting time (showing a correlation of 0.92).

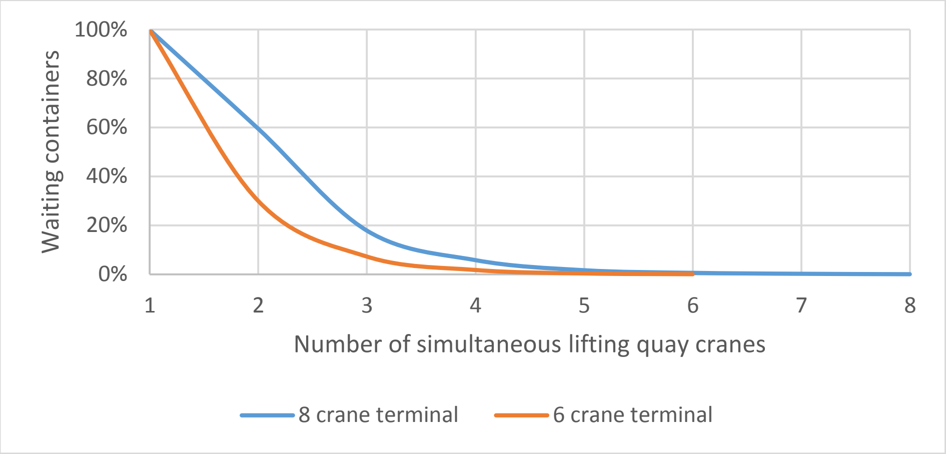

Figure 31: Percentage of delayed containers by reducing lifting quay cranes

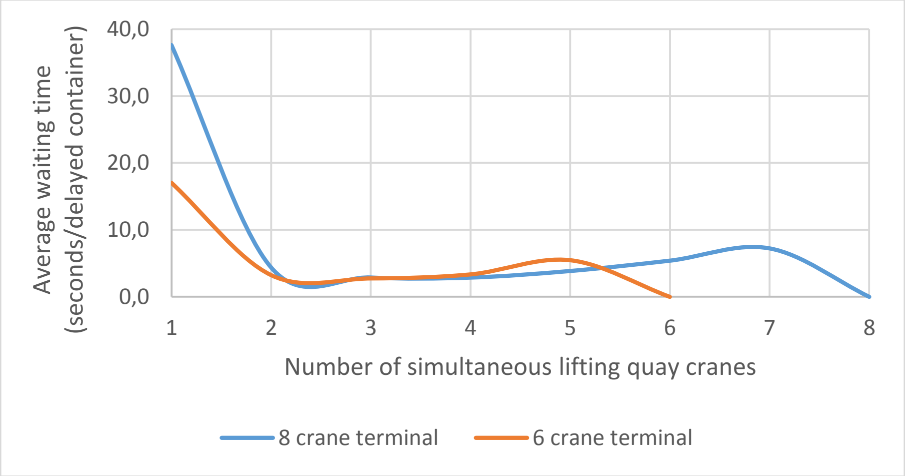

Figure 32: Average waiting time for delayed containers

When dividing the total savings per year by the total extra handling time, the total savings per extra second handling time can be determined. Figure 33 shows the result for this calculation. When looking to the 8-crane terminal (blue line), the most cost-effective scenario is to reduce the number of lifting cranes to 6, 5 or 4. In case of the 6-crane terminal, it is most cost-effective to reduce the number of lifting quay cranes to 5 or 4. In case of reducing the number of quay cranes to resp. 6, 5 or 4 (8-crane terminal) or to 5 or 4 (6-crane terminal), the chance that a container is delayed temporarily is between 0.3% - 5.7% (with an average waiting time of 0.02 - 0.17 seconds). The impact of this waiting of containers is considered limited due to the short waiting times and low number of waiting containers.

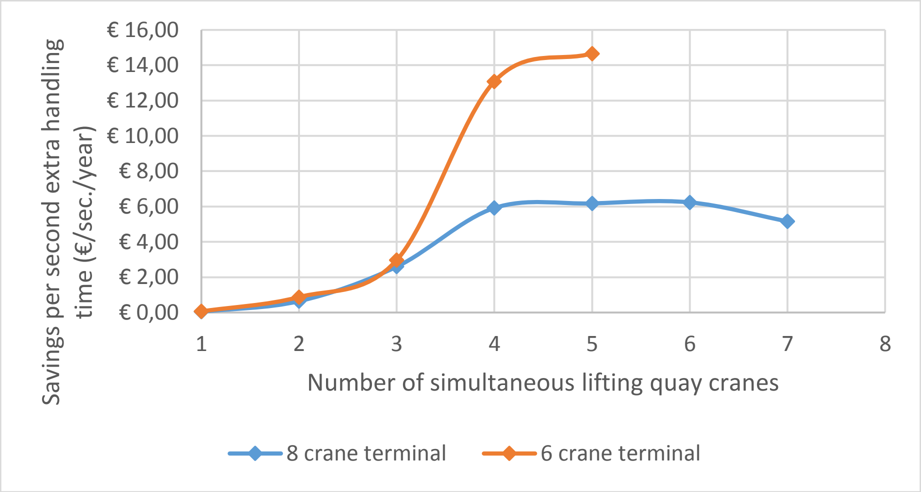

Figure 33: Savings per second extra handling time.

Conclusion

As concluded in this paragraph, restricting the number of simultaneously lifting quay cranes has a positive influence on the reduction of the peak demand. In this way the restriction of lifting quay cranes can be implemented in an operational environment to support container terminals to save costs against a relative low increase of handling time. A restriction which allows only half of the operational quay cranes to lift simultaneously has a limited effect on the handling time (maximum 0.44%), but saves the terminal up to €155,000 - €195,000 per year, which is approximately 40% of the peak related energy costs.

Because the waiting time increases exponential when limiting the number of simultaneously lifting quay cranes to more than half of the operational quay cranes, this seems no good idea. When looking to the savings per extra second handling time (see Figure 33), the potential savings per second decrease rapidly when reducing the number of simultaneously lifting quay cranes by more than 50%.

When looking to the most cost-effective scenario (i.e. yearly savings per extra second handling time) the most optimal implementation is to reduce the number of lifting quay cranes to 6, 5 or 4 (8-crane terminal) or to 5 or 4 (6-crane terminal) as can be seen in Table 10. In these cases the savings per extra second handling time are higher than for other scenarios. The 8-crane terminal is able to save €5.92-6.24 per second (total savings are €98,000 - €195,000 per year, which is 19% - 38% of the peak related costs), the 6-crane terminal might save €13.08 - €14.67 per year (total savings are €45,000 - €103,000 per year, which is 11% - 26% of the total peak related costs).

Table 10: Best scoring scenarios based on impact on handling time and savings per second

Low impact on handling time						
	Number of lifting cranes	**Total yearly savings (€/year)**	Savings per extra second (€/sec./year)	Extra handling time	Percentage of waiting containers	Average waiting time waiting (sec./waiting container)
8 cranes	4	**€ 195,000 (-38%)**	€ 5.92	0.37%	5.70%	2.88
6 cranes	3	**€ 155,000 (-39%)**	€ 2.96	0.44%	7.20%	2.76
Savings per extra second						
	Number of lifting cranes	Total yearly savings (€/year)	**Savings per extra second (€/sec./year)**	Extra handling time	Percentage of waiting containers	Average waiting time waiting (sec./waiting container)
8 cranes	6	€ 98,000 (-19%)	**€ 6.24**	0.18%	0.60%	5.41
	5	€ 150,000 (-29%)	**€ 6.18**	0.27%	1.60%	3.86
	4	€ 195,000 (-38%)	**€ 5.92**	0.37%	5.70%	2.88
6 cranes	5	€ 45,000 (-11%)	**€ 14.67**	0.03%	0.30%	5.48
	4	€ 103,000 (-26%)	**€ 13.08**	0.07%	1.70%	3.35

4.2 Limiting maximum energy demand

The restraining of energy demand contains the continuous checking of quay cranes whether they there is enough energy demand left to continue its operations. When for example a quay crane needs 1000kW and only 500kW is available due to the imposed maximum, the quay crane needs to wait until in total 500kW become available[11].

When analysing this rule of operation, the number of simultaneously lifting quay cranes is not restricted. The number of scenarios is determined by the highest peak demand that is observed for the 8-crane terminal (i.e. 19,200kW) and the 6-crane terminal (i.e. 14,940 kW). The lowest restriction is set at 4,000kW, since the maximum energy demand for one movement (i.e. the lifting of a spreader and 100% loaded container above the ships) is almost 3,000kW. A maximum allowed energy demand of 3,000kW would therefore delay the operations severely.

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[11] The simulation model is constructed in such a way that when a quay crane needs 1000kW and only 500kW is available, the available 500kW is 'seized' (i.e. reserved for this quay crane). After that the quay crane is seizing the first available extra 500kW, whereupon it can continue its operations.

Table 11: Scenarios for limiting the maximum energy demand for quay cranes

	Maximum energy demand (kW/s)	
	6 quay cranes	8 quay cranes
Base scenario	unlimited	unlimited
Limiting scenarios	15,000-4,000kW	20,000-4,000kW
Total number of scenarios	*13*	*18*

The results of the scenarios can be found in Table 12 and Table 13. When running the scenarios in the simulation model, the results show that the handling time is barely changing when restraining the maximum energy demand by 50% (as is also the case for restricting the number of lifting quay cranes). For the 8-crane terminal, the handling time is increasing more than 0.1% (i.e. more than 4 seconds extra per handling hour) when restricting the energy demand to 9,000kW per second. For the 6-crane terminal this is 8,000kW. While the handling time is barely influenced, the total savings range from €160,000 (8,000kW at 6-crane terminal) to €276,000 (9,000kW at 8-crane terminal). The half width of the peak demand is the same as for the limitation of the lifting quay cranes (i.e. 467.6 for the 8-crane terminal and 312.3 for the 6-crane terminal). A more detailed table with results can be found in 'Appendix F: Results simulation model'.

Table 12: Effect of limiting the maximum energy demand for 8-crane terminal

Energy demand limitation (kW/s)	**Peak demand (kW/s)**	**Handling time (hours/year)**	**Cost peak demand (€/year)**
(base scenario) unlimited	**19,230**	**2461.3**	**€518,000**
20,000	-0.2%	+0.0%	-€1,000
19,000	-2.3%	+0.0%	-€12,000
18,000	-6.9%	+0.0%	€36,000
17,000	-11.8%	-0.1%	€61,000
16,000	-16.9%	+0.0%	€88,000
15,000	-22.1%	+0.1%	€114,000
14,000	-27.2%	+0.0%	€141,000
13,000	-32.4%	+0.0%	€168,000
12,000	-37.6%	+0.1%	€195,000
11,000	-42.8%	+0.1%	€222,000
10,000	-48.0%	+0.1%	€249,000
9,000	-53.2%	+0.3%	€276,000
8,000	-58.4%	+0.5%	€302,000
7,000	-63.6%	+1.3%	€329,000
6,000	-68.8%	+3.2%	€356,000
5,000	-74.0%	+13.3%	€383,000
4,000	-79.2%	+44.6%	€410,000

Table 13: Effect of limiting the maximum energy demand for 6-crane terminal

Energy demand limitation (kW/s)	Peak demand (kW/s)	Handling time (hours/year)	Cost peak demand (€/year)
(base scenario) unlimited	**14,940**	**3277.4**	**€402,000**
15,000	-1.2%	+0.0%	€5,000
14,000	-6.6%	+0.0%	€27,000
13,000	-13.1%	+0.0%	€53,000
12,000	-19.8%	+0.0%	€80,000
11,000	-26.5%	+0.0%	€107,000
10,000	-33.1%	+0.0%	€133,000
9,000	-39.8%	+0.1%	€160,000
8,000	-46.5%	+0.2%	€187,000
7,000	-53.1%	+0.5%	€214,000
6,000	-59.3%	+1.1%	€241,000
5,000	-66.5%	+2.8%	€268,000
4,000	-73.2%	+13.4%	€295,000

When analysing the results in more detail, Figure 34 on next page visualises that the handling time is only increasing when the maximum energy demand is halved compared to the base scenario, while the peak demand decreases when restricting the energy demand per second. This is logical, since the cost savings are dependent on the highest observed peak. The sharp increase in handling time when reducing the energy demand too much can be explained by the fact that some movements consume up to 3,000kW/s. When restricting too much, only one or two of these movements can be done simultaneously, which delays the other containers. This can be seen in Figure 36 on page 54, where the number of delayed containers is visualised. Below 8,000kW/s the number of delayed containers increases almost exponentially.

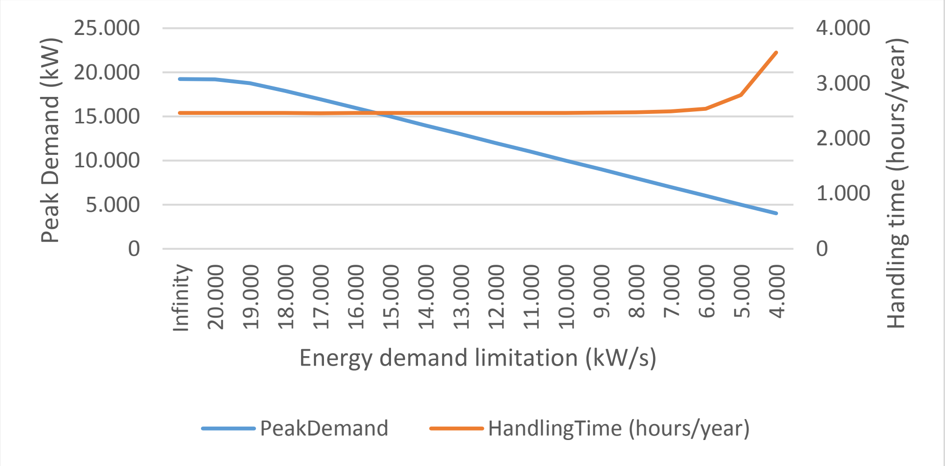

Figure 34: Relation between peak demand and handling time when restricting energy demand for 8-crane terminal

As shown in Figure 35, the relation between the cost savings and maximum allowed energy demand is very strong. The correlation of -1.00 shows that the potential savings always increase when the energy demand is restricted.

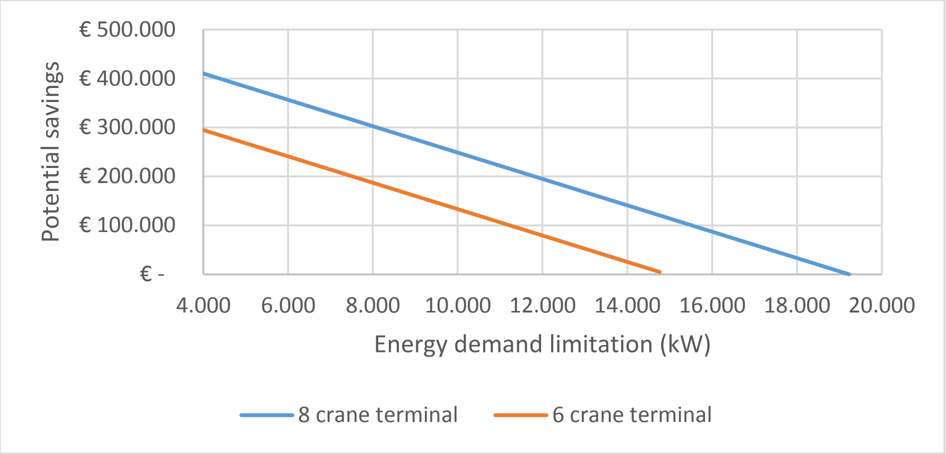

Figure 35: Potential savings per year for restricting maximum energy demand

Since the waiting time is not influenced that much when restricting the energy demand by less than 50% of the standard peak demand, the number of delayed containers is not high for these scenarios. When restricting the energy demand by 50%, only 2.2% (6-crane terminal) to 3.7% (8-crane terminal) are delayed for on average 3.4-3.5 seconds. The extra handling time is less than 0.1%, which shows the low impact of these delays. When restricting the energy demand by more than 50%, the percentage of delayed containers increases exponentially (see Figure 36), while the average waiting time is quite stable, until the energy demand is restricted too much (to 6,000kW or less, see Figure 37).

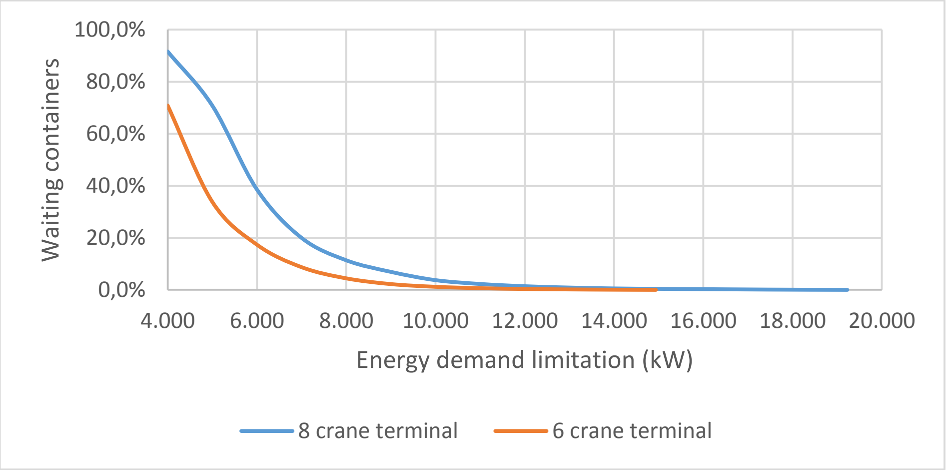

Figure 36: Percentage of delayed containers when restricting the energy demand

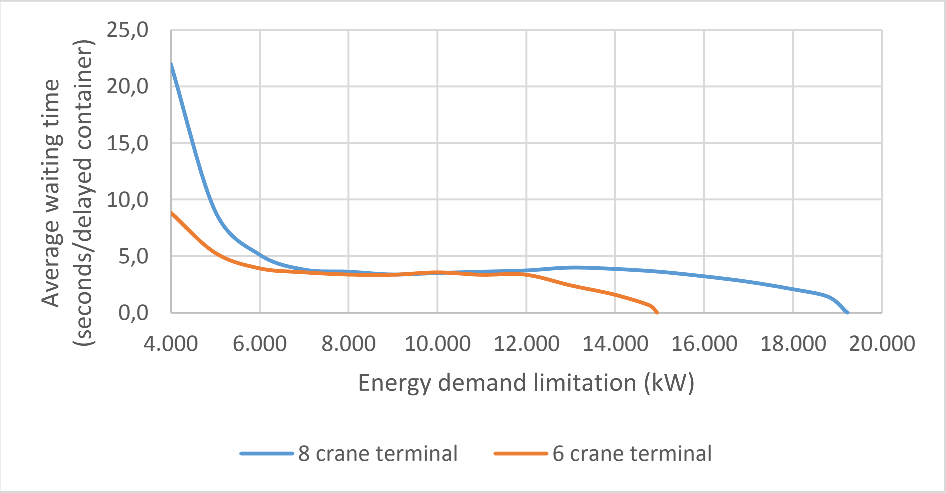

Figure 37: Average waiting time for delayed containers

When the total savings per year are divided by the extra handling time that is needed to handle all containers on a yearly base, the savings per second are obtained, as shown by Figure 38. For the 8-crane terminal there is a clear optimum when reducing the maximum demand to 14,000kW. In this case the savings are €141,000 per year, while the handling time is 0.01% faster. This results in a negative saving[12] of €197.10 per second. Restricting the energy demand to 17,000kW, 18,000kW or 19,000kW results also in a negative saving. However, in these cases the total savings are only €12,000 to €61,000. Restricting the energy demand to 13,000kW gives a saving of €251.53 per second, which the absolutely seen the highest saving.

For the 6-crane terminal the highest (negative) saving per second is obtained by reducing the maximum energy demand to 12,000kW (-€180.27 per second) or 13,000kW (-€115.86 per second), saving the terminal resp. €80,000 or €53,000 per year. The highest positive value (meaning a saving against extra handling time) is achieved by reducing the energy demand to 11,000kW. This saves €79.40 per second against an extra handling time of 0.01% and a total cost saving of €107,000.

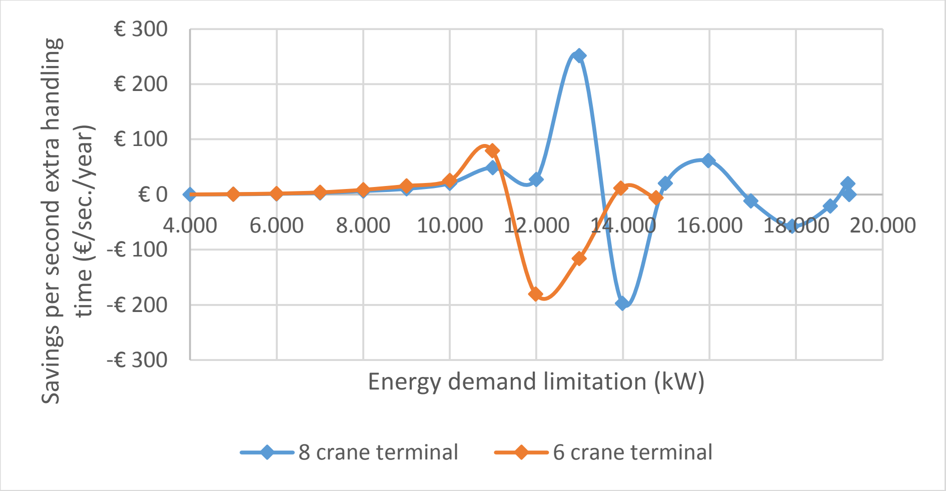

Figure 38: Savings per second extra handling time.

Conclusion

Derived from the described figures and tables, it can be concluded that decreasing the maximum allowed energy demand has a positive influence on the reduction of the terminals' peak demand. The influence on the handling time is only minimal when reducing the allowed energy demand by approximately 50%, while it enables container terminals to reduce their peak related energy costs by the same percentage, up to €250,000 per year. All results can be seen in Table 14.

When focusing on the most cost-effective result (i.e. yearly savings per extra second handling time) the most optimal implementation is to reduce the maximum energy demand to 14,000kW or 13,000kW for the 8-crane and to 13,000kW or 12,000 kW for the 6-crane terminals. For the 8-crane terminal this implies a negative saving of €197.10 per second or a saving of €251.53 per extra second, up to €168,000/year in total.

For the 6-crane terminal a reduction to 13,000kW or 12,000kW are a less cost-effective and the total savings are also relatively low (13% - 20% compared to the 27% - 32% of the 8-crane terminal). The handling time is hardly increasing, while the number of containers that is delayed by these scenarios is less than 0.3%.

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[12] The negative cost saving per second is actually a positive result, since the handling time for this scenario is lower compared to the standard situation, which means that the cost savings (positive result) are divided by a negative extra handling time (i.e. less handling time).

Table 14: Best scoring scenarios based on impact on handling time and savings per second

Low impact on handling time						
	Max. energy demand (kW)	**Total yearly savings (€/year)**	Savings per extra second (€/sec./year)	Extra handling time	Percentage of waiting containers	Average waiting time waiting (sec./waiting container)
8 cranes	10,000	**€ 249,000 (-48%)**	€ 20.12	0.1%	3.7%	3.5
6 cranes	9,000	**€ 160,000 (-40%)**	€ 15.53	0.1%	2.2%	3.4
Savings per extra second						
	Max. energy demand (kW)	Total yearly savings (€/year)	**Savings per extra second (€/sec./year)**	Extra handling time	Percentage of waiting containers	Average waiting time waiting (sec./waiting container)
8 cranes	14,000	€ 141,000 (-27%)	**€ -197.10**	0.0%	0.5%	3.9
	13,000	€ 168,000 (-32%)	**€ 251.53**	0.0%	0.9%	4.0
6 cranes	13,000	€ 52,000 (-13%)	**€ -115.86**	0.0%	0.2%	2.4
	12,000	€ 80,000 (-20%)	**€ -180.27**	0.0%	0.3%	3.4

4.3 Analysis of results

The outcomes presented in the first two paragraphs of this chapter show a clear outcome: it is possible to reduce the peak demand, saving up to €250,000 per year against a little extra handling time (in some scenarios without extra handling time). The bigger the restriction of the rules of operation, the larger the effect on the operations, visualised by the number of temporarily delayed containers (see Figure 31 and Figure 36 in paragraphs 4.1 and 4.2). However, since more and more container terminals are operating automatically, this can be integrated in the terminals' software. The delay of containers should be no problem when implementing one of the rules of operation.

4.3.1 Most-effective result

Regarding total cost savings, the optimal solution is to reduce the maximum energy demand per second by 50% of the original highest observed energy demand. By doing this, €160,000 - €249,000 (40% - 48% of peak related costs) can be saved annually. The impact on terminal operations are small, since the extra handling time is only 0.1% and the number of temporarily delayed containers is 2.2% - 3.7%. The savings per second are €15.53 - €20.12.

When the savings per second extra handling time are considered to be more important than the total annual savings (for example to compensate container carriers, see next paragraph), the maximum energy demand can be reduced by 30% - 35% (13,000 kW/s - 14,000kW/s) for an 8-crane terminal or by 5% - 15% for a 6-crane terminal (12,000 kW/s - 13,000kW/s). Because the handling time is hardly affected, the extra savings per second are very high, especially because some of these scenarios showed a small quicker handling time against a restricted energy demand.

When reducing the number of lifting quay cranes by 50%, the peak related costs are reduced by approximately 40% (saving up to €195,000 per year). The extra handling time is only 0.37% - 0.44% (less than half a minute per hour handling time) against a saving of €2.96 - €5.92 per second extra handling time. By reducing the number of simultaneously lifting quay cranes by less than 50%, the total savings are less, while the savings per second are not increasing. By reducing the number of lifting quay cranes by more than 50% the peak demand decreases even further, but the handling time increases drastically. The most optimal solution would therefore be to reduce the number of simultaneously lifting quay cranes by 50%.

4.3.2 Combining rules of operation

A combination of the described rules of operation would not result in higher or more effective savings, as concluded by a set of extra experiments. When focusing on the optimal annual savings, combining a reduction of 50% of the number of lifting quay cranes with a maximum energy demand of 10,000kW/s results in a less efficient outcome. This is because the peak demand of four lifting quay cranes at an 8-crane terminal lies around 11,000kW/s, which is higher than the restricted 10,000kW/s. However, while the peak demand stays the same (10,000kW) which does not results in extra savings, the handling time increases by 0.3%, which makes a combination less efficient. For the 6-crane terminal the same conclusion can be made.

When looking to the most optimal results for the highest savings per second, a reduction to five or sixlifting quay cranes at an 8-crane terminal leads to a peak demand of 13,500 - 15,500kW/s, which is higher than the optimal restriction in energy demand (13,000 - 14,000kW/s). Again the same conclusions can be made for the 6-crane terminal.

4.4 Implications of results

4.4.1 Extra handling time

The last paragraphs showed the financial benefits for container terminal when the energy demand or number of simultaneously lifting quay cranes is restricted. The handling time does not increase per se, however, a slight increase is to be expected. This means that the container terminals take the benefit of a lower energy bill, while the container carriers are the ones that have to accept extra handling time. The question is whether container carriers accept this extra handling time, since the benefits are fully for the container terminal while the disadvantage is for their account.

Extra waiting time for containerships is something that is watched critically by the container carriers. Shells Maritime Efficiency Manager, Leendert van den Ende, stated that unnecessary waiting time involves extra costs for them as charterer (Port of Rotterdam, 2013). Despite the critical attitude of cargo carriers towards waiting time in ports, the adaption of containerships' cruising speeds (also known as slow steaming) is no issue. For container carriers, their biggest costs are fuel. These costs might be reduced by adapting the ship speed: a reduction to 80% saves 60% fuel costs, while a reduction to 60% saves 90% of the fuel costs (Wärtsilä, 2010). A market survey showed that 75% of the surveyed liners and carriers apply slow steaming in order to save bunker costs (Seatrade Global, 2014). Since the fuel costs are that high, container carriers are operating more efficient when sailing at lower speeds. In this regard the extra travel time is compensated by fuel savings.

4.4.2 Costs containership

For handling 2,000 TEU of a containership (loading and unloading) a terminal needs approximately 18 hours using only three quay cranes. When extra handling time is needed, the question is whether container carriers are willing to accept this without any form of compensation. If terminal operations take more time than agreed in advance, carriers are compensated, known as demurrage (Haugen Consulting, 2015). When a ship requires less time than agreed on forehand, the terminal can request a bonus for quicker handling, the so called despatch. This shows that compensation is quite regular in the shipping business.

The question is therefore whether container terminals are able to compensate container carriers to a certain extent. To answer this question, first the costs for a containership need to be determined. To determine the annual costs for a containership, AECOM made a report for the North Carolina Department of Transportation (2012). They pointed out three cost aspects: the investment costs for a containership, labour costs and fuel costs. The purchase of a containership of 15,000 TEU (Emma Maersk class) costs around 127 million euros (Maersk, 2006). When dividing these costs over a lifespan of 30 years and an annual discount rate of six percent, this results in around 9 million euros per year. The labour costs can be estimated at 1.2 million euros (AECOM, 2012). Fuel costs can be neglected, since extra handling time will not lead to extra fuel consumption.

Table 15: Cost containership per year, hour and second

Type of cost	Costs
Investment costs	€ 9,000,000
Labour costs	€ 1,200,000
Total per year	**€ 10,200,000**
Total per hour	**€ 1,164**
Total per second	**€ 0.32**

Since a peak reduction of 50% saves a container terminal at least €2.96-5.92 per second (see paragraph 4.3.1), this leaves room to compensate the carriers for the extra handling time. This could result in a win-win situation: container terminals saving costs by reducing their peak demand and carriers reducing their handling costs due to the compensation.

4.5 Conclusion

The two rules of operations that are tested on their contribution to reduce the peak demand, showed that the peak demand can be reduced by almost 50%, while the handling time is only increasing slightly with maximum half a minute per hour handling time. This can be achieved by limiting the maximum energy demand to 50% of the peak demand that is observed in the normal situation (i.e. without restrictions of one or more rules of operation).

By restricting the maximum energy demand per second, a container terminal is able to set a ceiling on the energy demand, which means that each quay crane needs to get ‘permission’ before executing one of its movements. If there is not enough energy left to execute a particular movement, a container is temporarily delayed. However, the percentage of containers that is temporarily delayed is less than 3.7% when reducing the energy demand limit by 50%.

The limitation of simultaneously lifting quay cranes is also successful to reduce peak demand. Most savings are achieved by reducing the number of simultaneously lifting cranes to 50% of the total number of cranes at the container terminal. However, the savings for this rule of operation are 10% lower than for limiting the energy demand. Next to that, the impact on operations (percentage of delayed containers) is 5.7%, which is 2.0% higher than for limiting the energy demand by 50%.

In this way, both rules of operation can be recommended for peak shaving the electricity demand at container terminals (sub-question 7). However, the restriction on the maximum energy demand is able to reduce the costs by 50% without influencing the handling time by more than half a minute per hour handling time.

Barges and large containership docked at the Euromax terminal, Port of Rotterdam
Photo: Marijn van Hoorn (Flickr, 28 June 2012)

5. Conclusions and recommendations

In this research the container terminal operations are discussed (chapter 2), leading to the development of an energy consumption model and a simulation model (chapter 3). The results of the simulation study are subsequently described and discussed (chapter 4). In this chapter the research is concluded in paragraph 5.1, presenting the most remarkable findings. Based on the findings of this research, several recommendations and directions for future research are given in paragraphs 5.2 and 5.3.

5.1 Conclusions

The research has shown that it is possible to smoothen the peak demand of a container terminal by implementing rules of operation. These rules act as 'controllers' that smoothen the energy demand by limiting the cause of high peaks. Two rules are studied: less quay cranes that lift simultaneously and limiting the movements of quay cranes by putting a maximum on the energy demand per second).

The effects of the suggested rules of operation can be measured in two ways[13]:

- Maximum total savings for terminal
  Finding the optimum of cost savings based on savings and acceptable[14] extra handling time.
- Cost-effectiveness terminal
  Finding the maximum savings based on savings per extra second handling time.

When applying the energy consumption model for a container terminal with 6-8 quay cranes, the following results are shown for the two tested rules of operation:

- Limiting simultaneously lifting quay cranes

The number of simultaneously lifting quay cranes can be reduced by 50%, impacting the handling time less than 0.5%. By reducing the number of simultaneously lifting quay cranes to 50%, a peak shaving and cost reduction of 39% can be achieved, as shown by Table 16. The impact on operations is then maximum 0.44%. The number of simultaneously can be reduced even more, but the handling time would then increase exponentially and almost one out of five containers would be delayed temporarily. By reducing the number of simultaneously lifting quay cranes by 50%, one out of 20 containers would be delayed temporarily. This shows that terminal operations are quite stable when reducing the number of simultaneously lifting quay cranes by 50%. This is understandable since not all quay cranes are continuously executing a lifting movement at the same time. The restriction is therefore not restricting quay cranes during the whole time of operations.

When focussing on the savings per second, an optimum is found when reducing the number of simultaneously lifting quay cranes to 6 cranes (8-crane terminal) or 5 cranes (6-crane terminal). In these scenarios the peak

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[13] The savings are derived from the reduction in peak demand; the higher the savings, the higher the reduction in peak demand). A reduction of 10% in peak demand returns a cost saving of 10%. In most situation the cost savings will be described, since the ultimate objective for container terminals is to reduce their peak-related costs.

[14] When one only focuses on cost reduction, the peak demand can be reduced in such a way that the handling time is increasing enormously. Therefore a certain 'limit' has to be set, to find a feasible result.

demand is reduced by 11% - 19% and the savings per second count up to €14.67 per extra second handling time per year. A terminal can choose for this scenario when the savings per second are more important than the total savings, since a reduction of simultaneously lifting quay cranes by 50% results in less savings per second.

Table 16: Optimal results for limiting number of simultaneously lifting quay cranes

Maximum total savings for terminal					
	Number of lifting cranes	**Total yearly savings (€/year)**	Savings per extra second (€/sec./year)	Extra handling time	Percentage of waiting containers
8 crane terminal	4	**€ 195,000 (-38%)**	€ 5.92	0.37%	5.70%
6 crane terminal	3	**€ 155,000 (-39%)**	€ 2.96	0.44%	7.20%
Maximum savings per extra second handling time					
	Number of lifting cranes	Total yearly savings (€/year)	**Savings per extra second (€/sec./year)**	Extra handling time	Percentage of waiting containers
8 crane terminal	6	€ 98,000 (-19%)	**€ 6.24**	0.18%	0.60%
6 crane terminal	5	€ 45,000 (-11%)	**€ 14.67**	0.03%	0.30%

- Limiting maximum allowed energy demand

When reducing the maximum allowed energy demand (kW/s) to 50% of the standard maximum observed peak demand, the handling time is increasing with maximum 0.1% (less five seconds per hour handling time). This low impact on handling time is caused by the fact that an energy demand of more than 50% is only needed 1.1% of the time, as visualised in Figure 39. The negative energy demand occurs when more power is generated than consumed, for example when quay cranes are lowering a container.

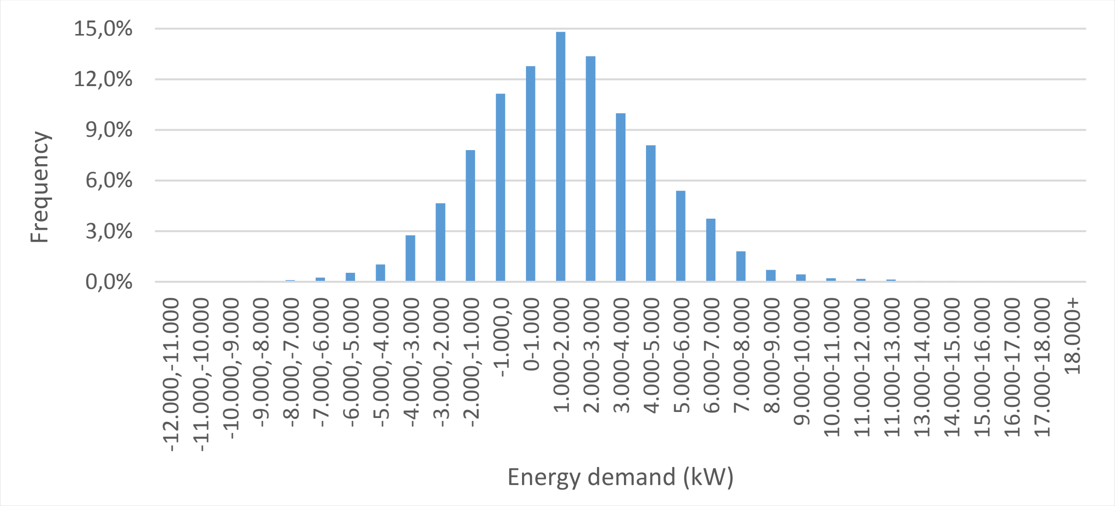

Figure 39: Frequency graph for energy demand during operations (measured per 0.1s)

The most optimal solution based on maximum total savings without impacting the handling time more than 0.1% is to reduce the maximum energy demand by 40% - 48%, as shown in Table 17 on next page. The savings per second are higher when reducing the maximum energy demand by 20% - 27%, which is caused by the fact that the handling time is not affected, and in some situations even reduced, while the peak demand decreases. This means that costs are saved without extra handling time. The impact of delayed container is in these situations maximum 0.5%.

Table 17: Optimal results for limiting maximum energy demand

Maximum total savings for terminal					
	Max. energy demand (kW)	**Total yearly savings (€/year)**	Savings per extra second (€/sec./year)	Extra handling time	Percentage of waiting containers
8 crane terminal	10,000	**€ 249,000 (-48%)**	€ 20.12	0.1%	3.7%
6 crane terminal	9,000	**€ 160,000 (-40%)**	€ 15.53	0.1%	2.2%
Maximum savings per extra second handling time					
	Max. energy demand (kW)	Total yearly savings (€/year)	**Savings per extra second (€/sec./year)**	Extra handling time	Percentage of waiting containers
8 crane terminal	14,000	€ 141,000 (-27%)	**€ -197.10**	0.0%	0.5%
6 crane terminal	12,000	€ 80,000 (-20%)	**€ -180.27**	0.0%	0.3%

Implications

The potential reduction of the peak related energy costs is around 40% - 48% when reducing the energy demand by 50% of the highest observed peak demand in a standard situation without restrictions. When reducing the number of simultaneously lifting quay cranes a peak reduction and corresponding cost saving of 38% - 39% can be achieved. An extra handling time of max. 0.44% saves a container terminal with a yearly throughput of 1,600,000 million TEU €155,000 - €249,000 per year. With a worldwide container port throughput[15] of 580 million TEU (UNCTAD, 2013), this could save container terminals all over the world a tremendous 56-90 million euros per year.

The extra handling time of max. 0.44% can be a problem when container carriers are not accepting extra handling time. In these situations the terminal needs to negotiate and compensate for the extra handling time. This is feasible, since the savings per extra second handling time seems to be higher than the costs for a containership. When terminals are willing to save more costs per second handling time, an optimum is found by implementing the rules of operations less strict. This would save them around 20% of the peak demand and costs, against less extra handling time.

5.2 Recommendations

Focusing on the maximum savings is more profitable, but has also more impact on the terminal operations, since the number of containers that is shortly ceased during the operations is higher than for the most cost-effective optima. Now the potential savings are presented, the container terminals have to consider which extra handling time is acceptable, given the potential peak reduction and corresponding cost savings. This leads to the following recommendations:

- **Implementing smart management system**
  Container terminals can reduce their normal peak demand by almost 50%, saving them up to €249,000 peak related costs per year when the maximum allowed energy consumption per second is reduced by 50%. A limitation of the number of simultaneously lifting quay cranes has a lower total saving and has more impact on the terminal operations. Both rules of operation can be implemented on a terminal by a smart management system (see paragraph 2.4.1), which controls the maximum energy demand or number of simultaneously lifting quay cranes.
- **Pilot project**
  The current results are based on a simulation model which studies several different assumptions (see chapter 3.3.5). Some assumptions showed a significant impact of around 14% (average TEU/movement) and some assumptions did not show significant effects (i.e. effect of ceasing containers temporarily during their movement on energy demand). To refine the presented results, the model need to be

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[15] The world container port throughput is higher than the worldwide transport of containers. This is because containers are also transhipped between ports. This means that one 20ft. container counts as 1 TEU for the worldwide transport and might count more than one time for the port throughput if handled several times. In 2011 the port throughput was 540 million TEU and the worldwide transport 153 million TEU. This means that a container is handled 3.5 times on average.

applied as a pilot project on a container terminal. In this environment real results can be gathered and analysed, which give a more reliable outcome of the potential results.

- **Investigate support container carriers**
  Investigate the support of container carriers for a higher handling time. It can be expected that they are not willing to delay the handling operations for their containerships. Container terminals need to be prepared to negotiate with container carriers about some sort of compensation. This can be financially, but also regarding extra service (e.g. free electricity power for ships while berthed) or sustainability agreements.
- **Broader application of rules of operation**
  Next to STS cranes and other terminal equipment, the energy consumption model can also be applied in other industries who use equipment that is dependent on transportation movements. For these companies the implementation of certain rules of operation can be beneficial to reduce their peak demand.

5.3 Directions for future research

Based on the research and its recommendations, the following directions for future research can be identified:

- Further validation of the developed simulation model in order to have a better view on the impact of the assumptions that are made. More accurate data will be needed for this, so a collaboration with a container terminal in a pilot project might be helpful (see recommendation on pilot project).
- Application of energy consumption model for fully-electric operating container terminals to enable a deeper investigation to the influence of the different terminal processes on the peak demand of container terminals. In this study the consumption model was applied for a container terminal which had only one type of electrical terminal equipment: quay cranes. For fully-electrical operating terminals the model can be applied for other electrical terminal equipment like the Automated Stacking Cranes and rail cranes.
- Extension of energy consumption model to include all electrical consuming terminal processes, like for example the reefers, lighting, buildings and the loading of batteries for AGVs. The energy use of reefers is very interesting, because the share of reefers is growing yearly and only little is known about the dynamic of their energy use and influence on the terminals' peak demand.
- Research towards energy consumption of a quay crane to investigate whether the energy consumption of particular movements can be reduced by for example changing the acceleration of the quay crane.

Ship leaving the Port of Rotterdam
Photographer unknown

6. Reflection

The reflection in this chapter presents several of my personal findings on several aspects of the research. First the methodology is discussed, followed by the data and validation, case study and the results of experiments.

Methodology

For simulating the quay crane environment of a container terminal, a discrete-event simulation is applied. The advantage of this method is the event-based character which facilitates the simulation of containers that are transported and can be seen as passive objects running through a model. The two other alternatives, agent-based modelling and system dynamics, do not provide for this.

I am satisfied about the use of Simio as software for constructing the simulation, despite taking more time than expected to master the program, since it was my first time using this software. The elaborate possibilities to connect several processes to an entity state change were useful for tracking and statistical purposes. However, in order to be able to get all needed statistics out of the model, lots of these processes were made. This makes it hard to explain the exact way the model works to others that are willing to work with the simulation model.

In first instance I constructed the simulation of the quay cranes based on the six main movements. However, when new data became available during the development, every movement needed to be modelled in two to three sub-movements. I did this by extending the six existing server blocks to seventeen server blocks. Although this was the fastest way to change the model, the best way would maybe be to include the two or three sub-movements per different movement within the existing process server. A deeper understanding of Simio would have contributed to a better modelling solution.

Data and validation

A major challenge was the comprehensive data collection needed to develop and validate the simulation model. Because the simulation model is dependent on a specific terminal layout and a specific collection of operational terminal equipment, the simulation is based on an existing container terminal that serves as case-study. This means that the collaborating data should be collected from that particular container terminal as much as possible. Therefore the research was very dependent on the willingness of a terminal to collaborate, which was hard because of the strong competitive position within the container terminal business. Luckily some data was available via the GREEN EFFORTS project. This was the reason for applying the case-study for the MSC terminal in Valencia. However, the assumptions that needed to be made would affect the reliability of the outcome of the simulation model too much. Therefore I was glad that new data of ABB came available for my project, so a better simulation study could be developed, resulting in a more reliable outcomes.

Because previous research did not focus on the energy demand per second, I needed to develop an energy consumption model that was able to do so. However, it is hard to validate the model with real results, since the container terminals are not sharing their energy consumption data. Although the energy demand could be visualised quite accurately, based on the validation with the ABB-data, the model is not tested in a real terminal environment, which is a pity in my eyes.

Case study

For applying the developed energy consumption model I worked with the terminal configuration of the MSC terminal in Valencia. It is a pity that in the stage of developing the simulation study no other data was available, because now I was limited to apply the consumption model for only the quay cranes. This meant that I needed to demarcate the model in a small way, by not being able to include other electrical terminal equipment (e.g. ASCs) in the simulation.

Results of experiments

To analyse the results a problem arises when I tried to find the 'best' solution. The main research question was to find rules of operation that contribute to a reduction of the peak demand, while monitoring the consequences for the handling time. The developed rules of operation could be implemented in several ways: reducing the quay cranes from 8, to 7, 6 or less, or reducing the maximum energy demand per second from 18,000 to 17,000, 16,000 etc. In order to be able to find one or more 'best solutions', I introduced two criteria: the most cost-effective solution (€/kW/year) and the most cost-beneficial solution (€/year) against a maximum extra handling time of 2.5%. This 2.5% is chosen by myself and unfounded by any expert or source, since it is not known which maximum extra handling time terminals are willing to accept. This problem aroused during one of the last weeks of the research. If I would have seen this problem coming, I would pay more attention to the way the most optimal result can be found.

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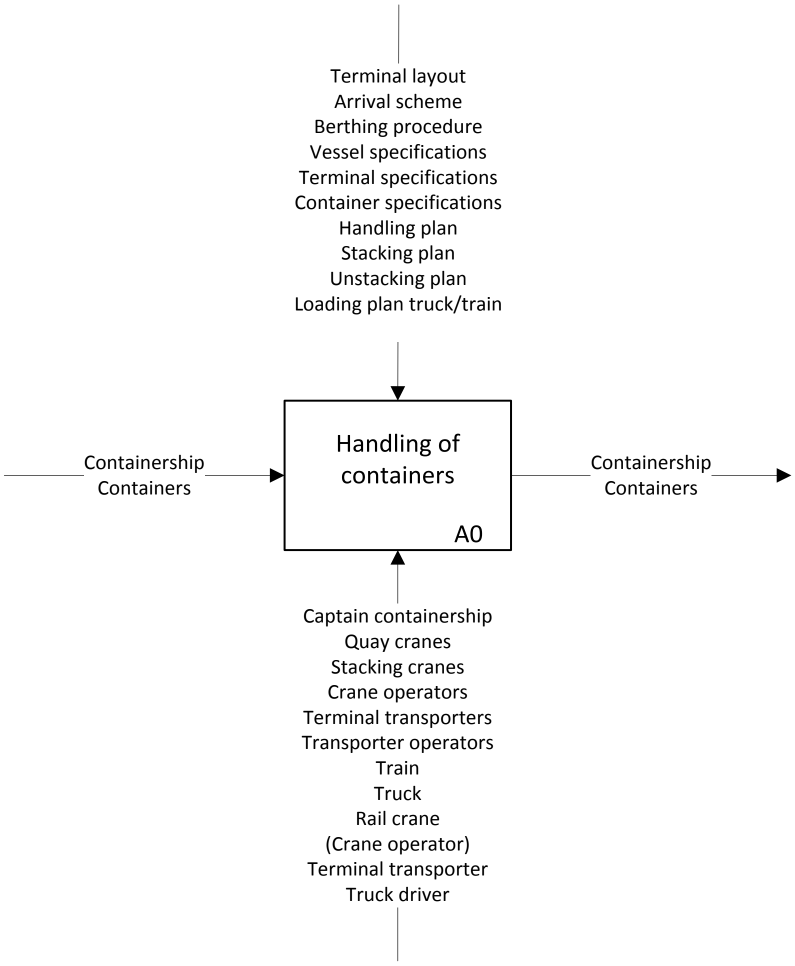
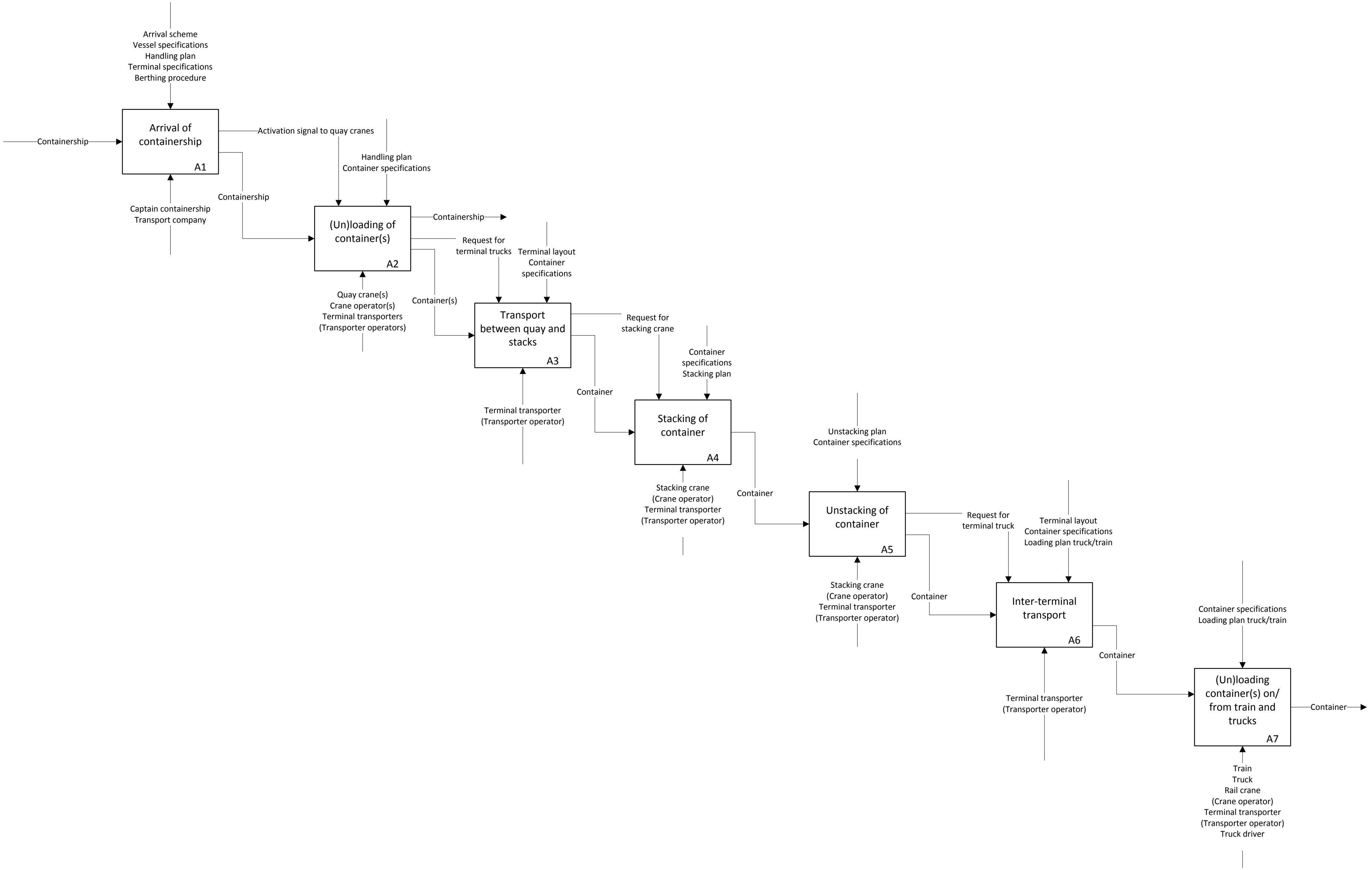
Appendix A: IDEF0 Process schemes

In this appendix the IDEF0 process schemes are presented as described in chapter 2. First the A0 scheme can be found, followed by the first decomposition where all main processes are described. This scheme is further decomposed into the sub-process schemes of A1-A7.

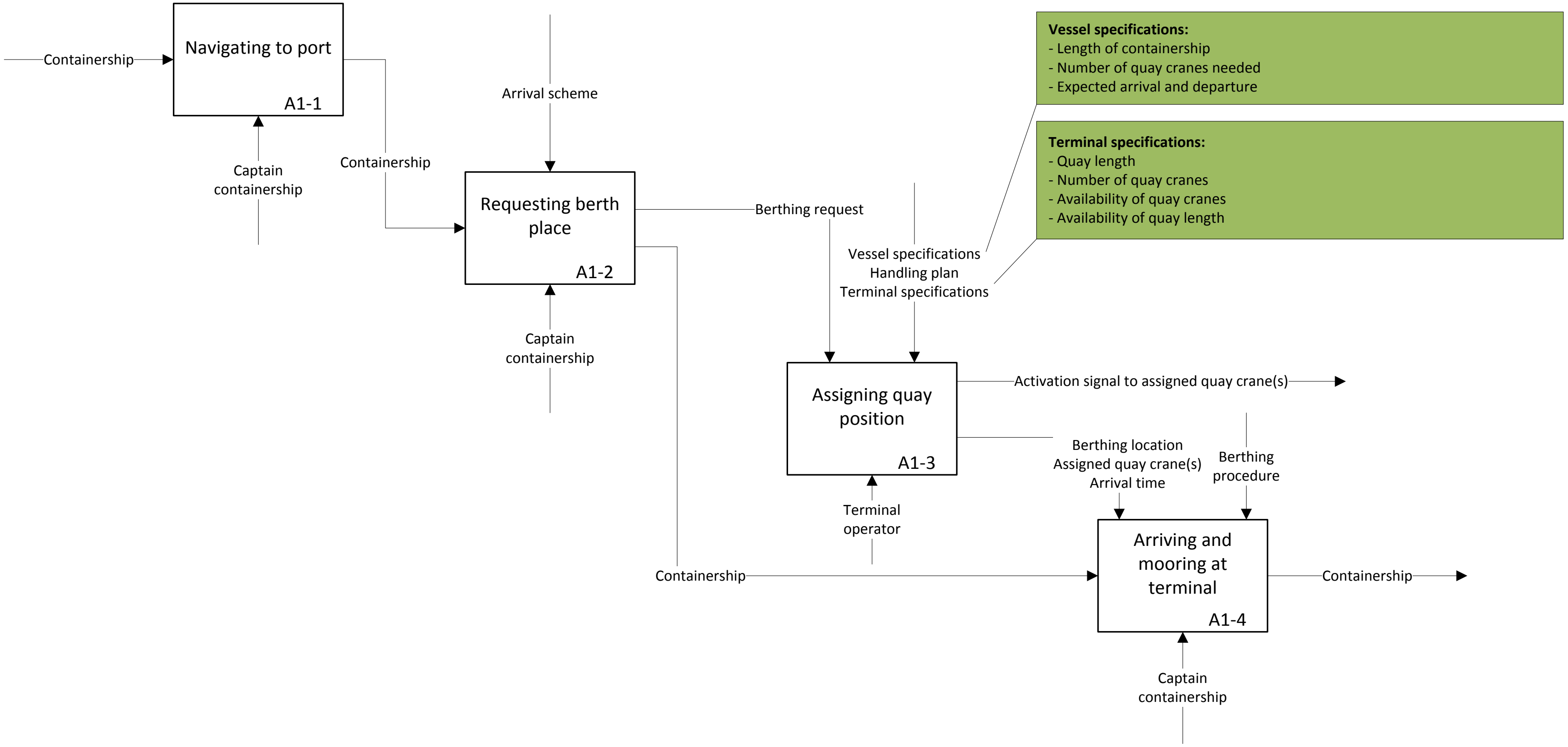


Decomposition of A0 – Processes A1-A7



- The sequence of the above presented processes (A1-A7) is a common order of processes. However, the order might change, for example in case of containers that enter the terminal via train/truck (A7-A3-A4) or containers that are unstacked and then transported to a containership (A5-A3-A2).

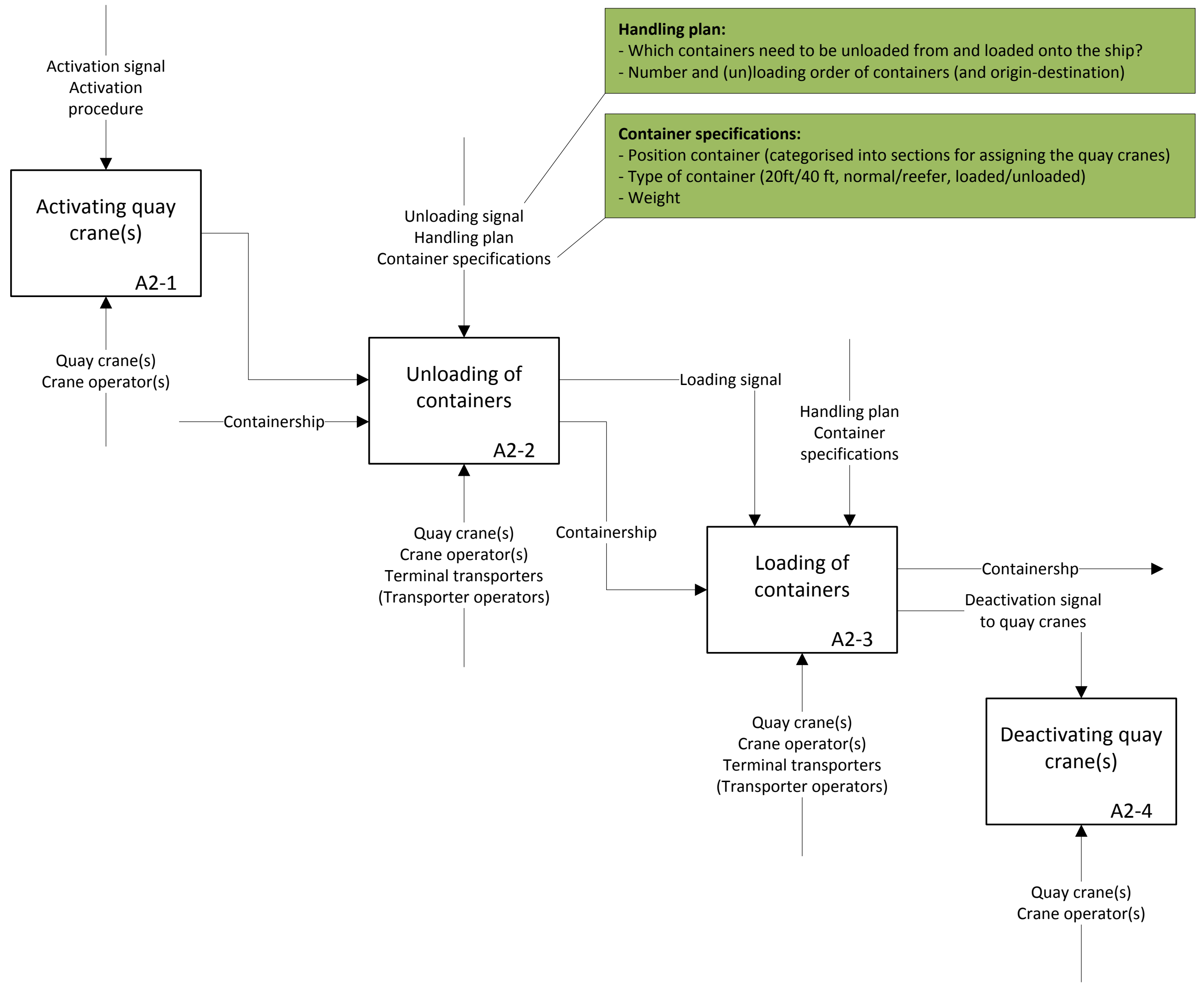
Decomposition of A1 – Berthing process



Vessel specifications:
- Length of containership
- Number of quay cranes needed
- Expected arrival and departure

Terminal specifications:
- Quay length
- Number of quay cranes
- Availability of quay cranes
- Availability of quay length

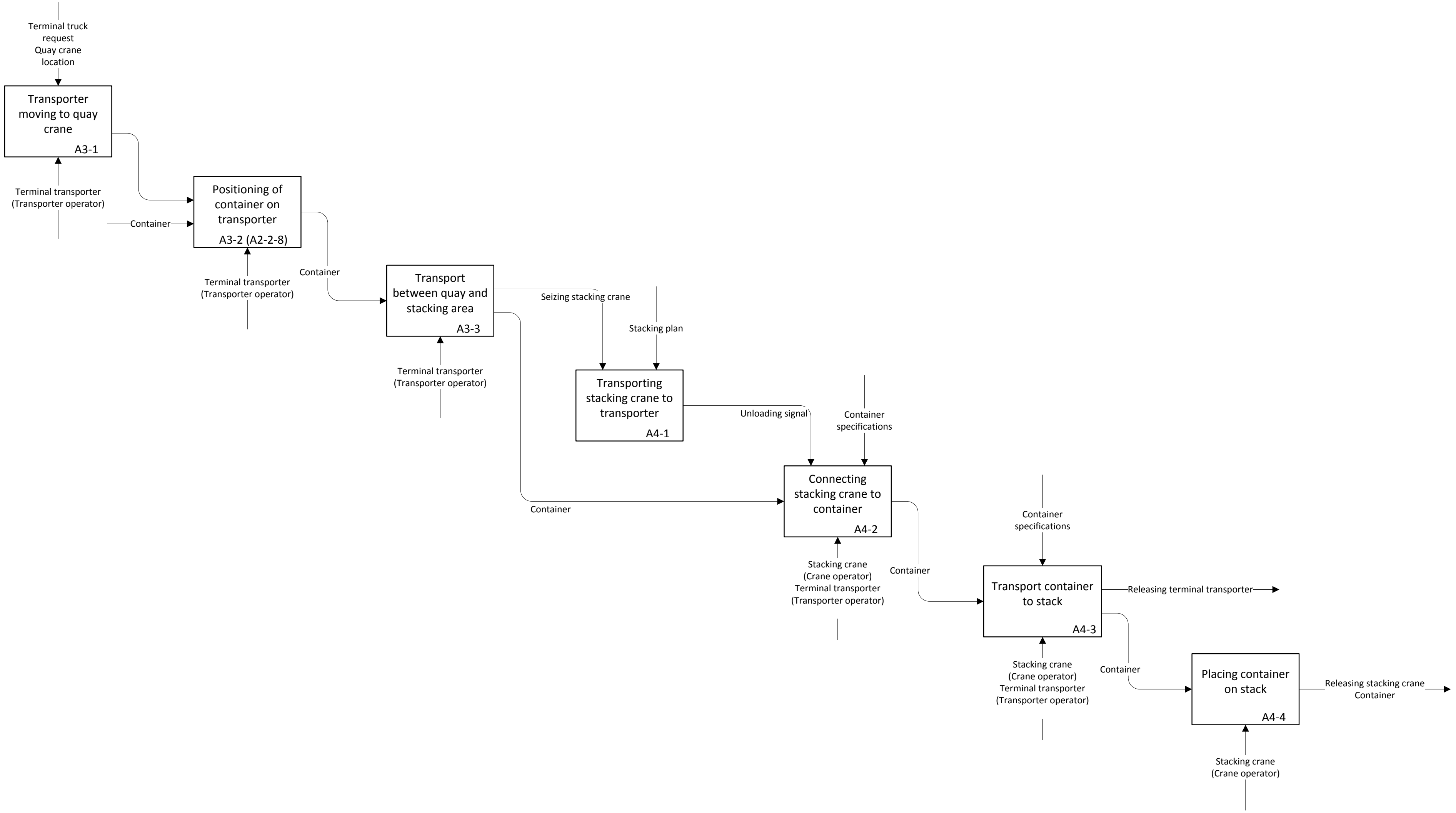
Decomposition of A2 – (Un)loading of containers at quay side



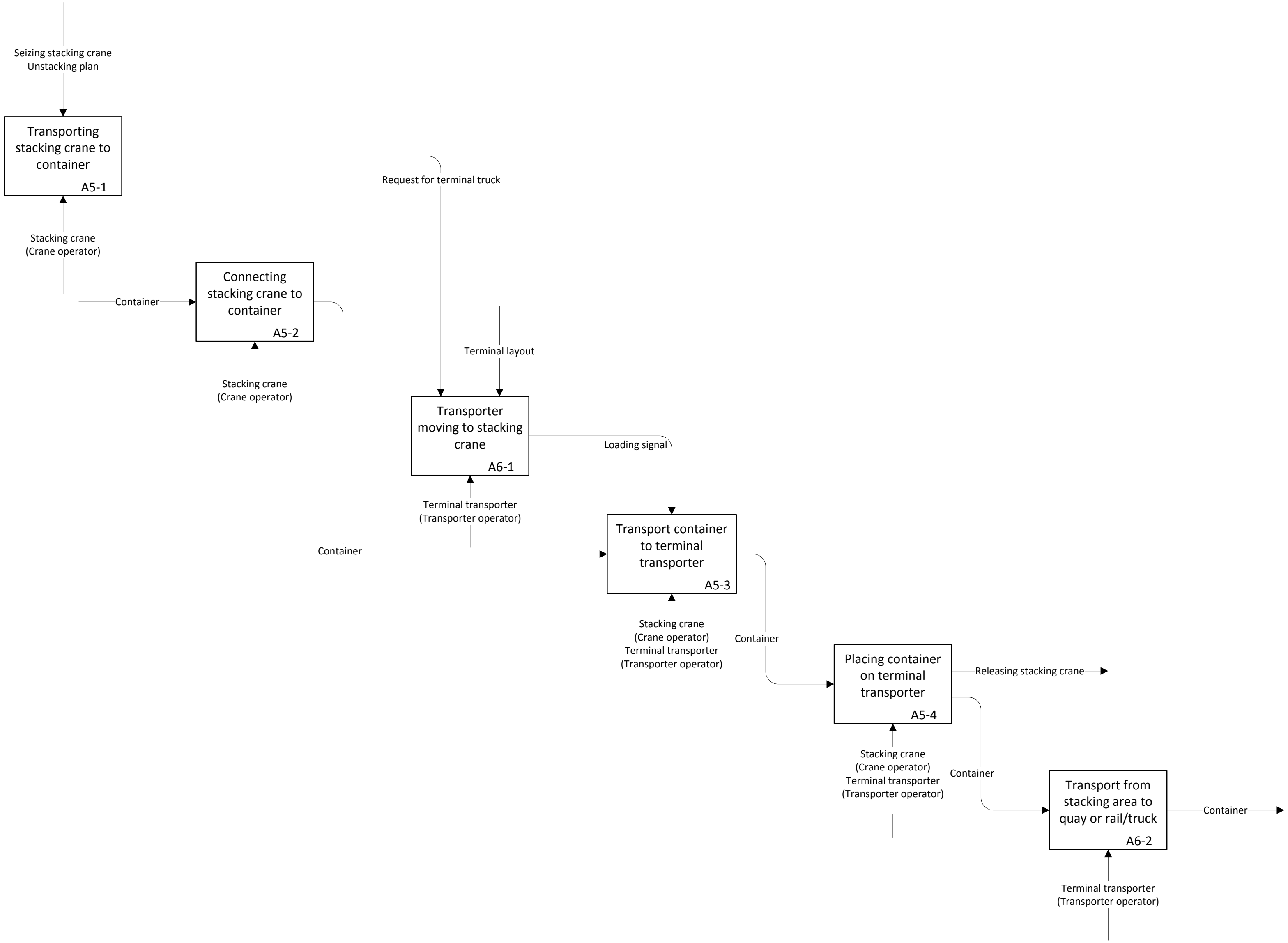
Handling plan:
- Which containers need to be unloaded from and loaded onto the ship?
- Number and (un)loading order of containers (and origin-destination)

Container specifications:
- Position container (categorised into sections for assigning the quay cranes)
- Type of container (20ft/40 ft, normal/reefer, loaded/unloaded)
- Weight

Decomposition of A3 & A4 – Transport to stacking area and stacking of containers

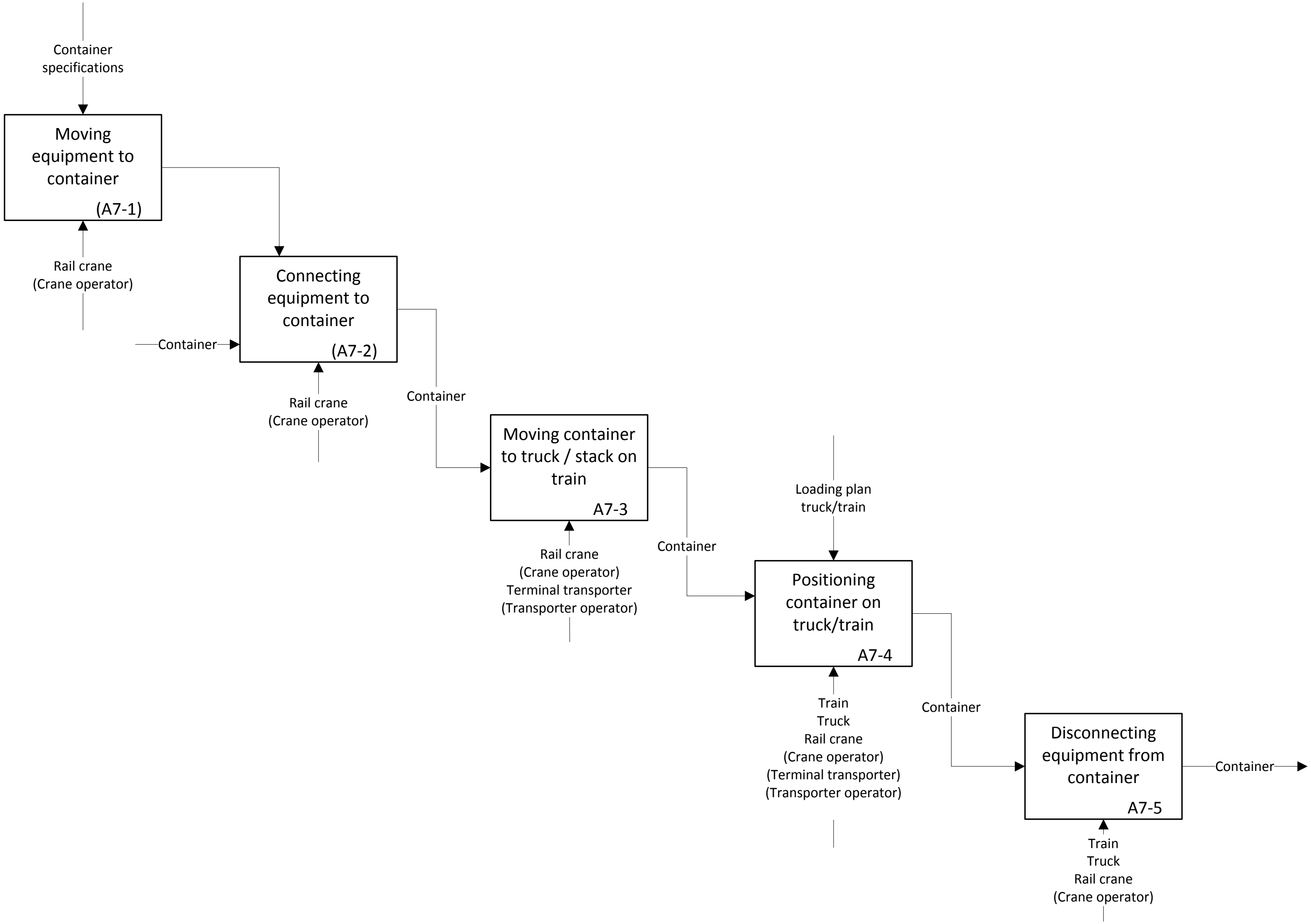


Decomposition of A5 & A6 – Unstacking of containers and transport to trains/trucks



- The A5 process (unstacking container) and A6 process (requesting terminal equipment and transporting the container) intermingle.
- The exact sequence of processes is dependent on the type of equipment that is used. This process scheme represents the most common used process.

Decomposition of A7 – (Un)loading containers on and from trains/trucks



The A7-1 and A7-2 processes are dependent on the type of equipment that is used. In the following cases these two processes are not executed:

- Trucks: the containers are often positioned on the truck with the same equipment as used for transport to the truck (same for unloading)
- Trains: when the containers are positioned on the train with a reach stacker and this reach stacker is also used for transport from the stacking area to the train

Appendix B: List of required data for consumption model

This appendix gives a detailed list of the data that is needed for the application of the energy consumption model that is described in chapter 3. The data is explained in general in paragraph 3.2.

The general data that is needed concerns:

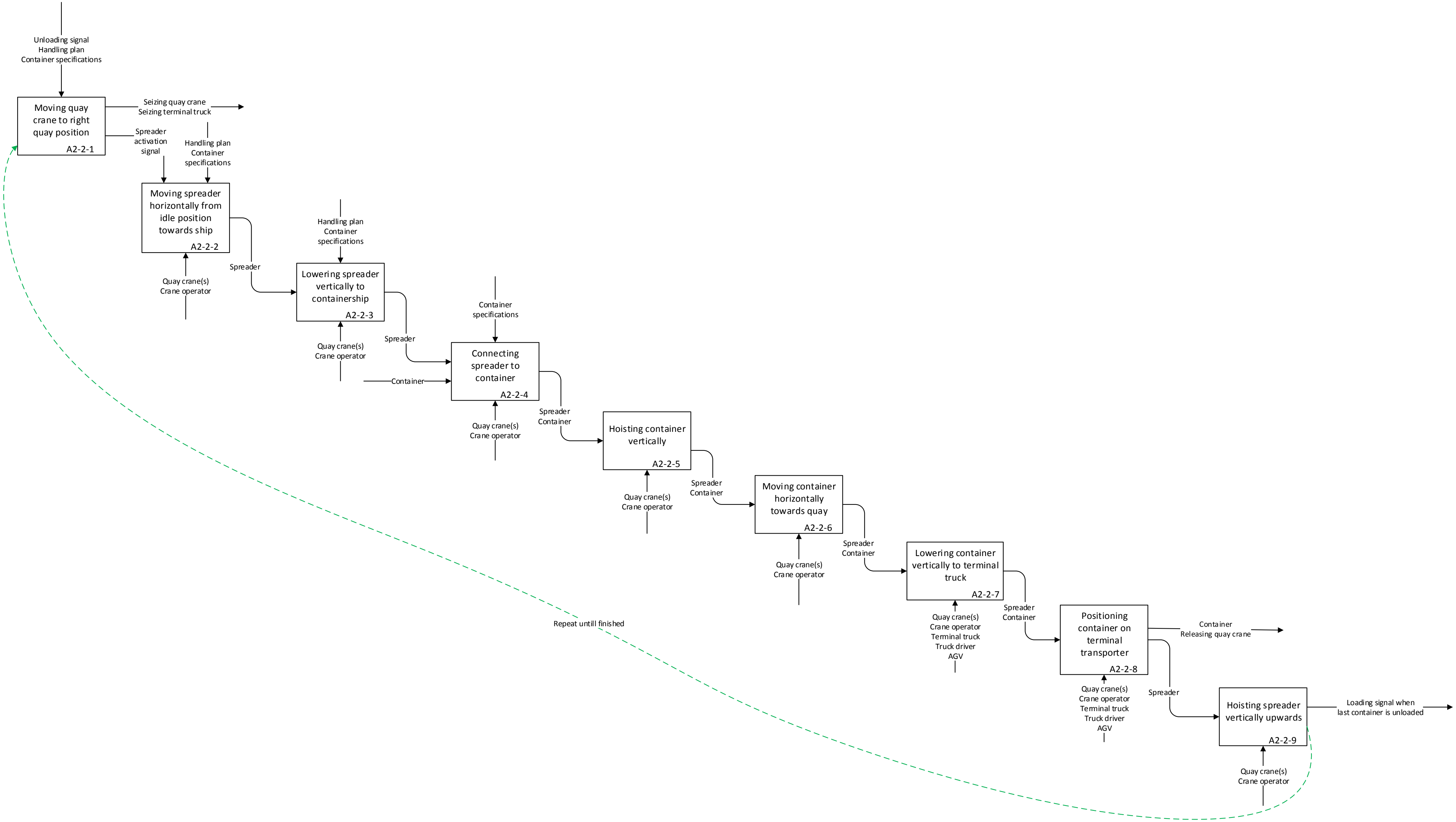
- terminal layout specifications (i.e. number of quay cranes);
- arrival scheme containerships;
- number of containers to be handled;
- container load specifications;
- position of containers;
- energy consumption specifications (kW/s).

Terminal equipment

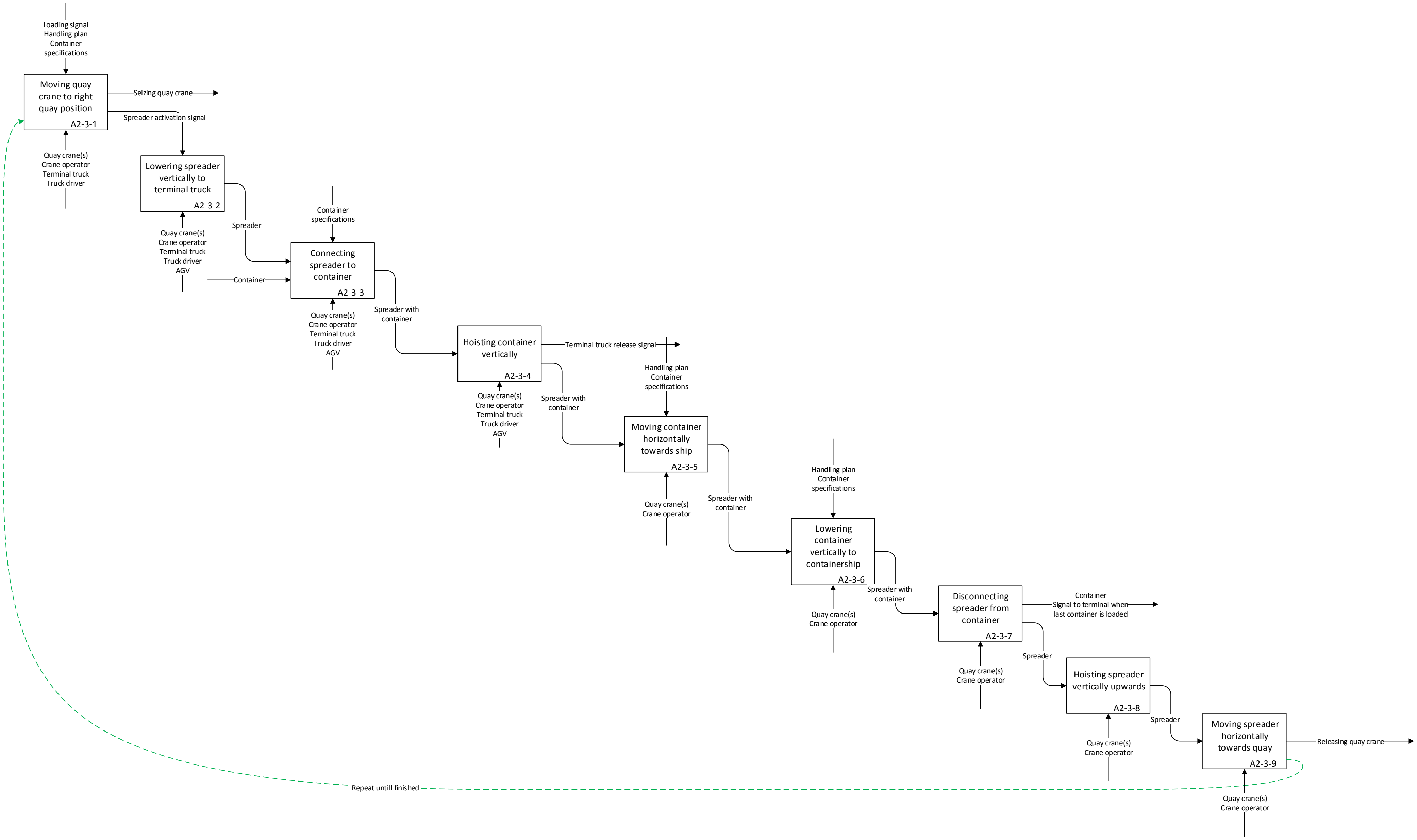
- Terminal layout configuration
- Quay cranes / rail cranes
    - Type and number of quay cranes (and barge cranes)
    - Number of moves per crane
    - Energy consumption idle state (kW/s)
    - Energy consumption busy state (kW/s)
        - Horizontal movement of spreader
        - Hoisting the spreader
        - Lowering the spreader
        - Movement of quay crane on quay
    - Auxiliary energy specifications (e.g. lighting, steer cabin)
    - Layout specifications of terminal (to determine distances)
- Terminal transporters
    - Type and number of transporters
    - Number of moves per transporter
    - Energy consumption idle state (kW/s)
    - Energy consumption busy state (kW/s)
        - Movement of transporter over terminal
        - (Hoisting spreader/container)
        - (Lowering spreader/container)
    - Auxiliary energy specifications (e.g. lighting, steer cabin)
    - Layout specifications of terminal (to determine distances)
- Stacking cranes
    - Type and number of stacking cranes
    - Number of moves per stacking crane
    - Energy consumption idle state (kW/s)
    - Energy consumption busy state (kW/s)
        - Movement of crane over terminal
        - Horizontal movement of spreader
        - Hoisting spreader
        - Lowering spreader
    - Auxiliary energy specifications (e.g. lighting, steer cabin)
    - Layout specifications of terminal (to determine distances)

Appendix C: IDEF0 process schemes for (un)loading containers

Decomposition of A2-2 – Unloading containers from containerships



Decomposition of A2-3 – Loading containers onto containerships



Appendix D: Arrival scheme containerships

The arrival scheme that is used for simulating the MSCTV is shown in Table 18. Here an overview of the number of containerships and corresponding number of containers (expressed in TEU and 40ft equivalents) can be found.

Table 18: Arrival scheme with number of containers per containership

Number containership	Start operations	Number of TEU	Number of (40ft.) containers
1	1/12/2012 08:18:28	322	161
2	1/12/2012 08:45:12	585	293
3	1/12/2012 22:11:28	966	483
4	2/12/2012 02:20:48	666	333
5	2/12/2012 20:19:07	3805	1903
6	3/12/2012 14:15:57	1869	935
7	4/12/2012 02:26:32	641	321
8	4/12/2012 14:23:14	1547	774
9	4/12/2012 20:17:01	1026	513
10	5/12/2012 08:22:03	532	266
11	5/12/2012 08:54:47	1068	534
12	5/12/2012 14:18:04	618	309
13	6/12/2012 01:29:30	696	348
14	6/12/2012 08:09:58	1716	858
15	6/12/2012 14:21:55	348	174
16	6/12/2012 20:17:37	737	369
17	6/12/2012 23:35:59	303	152
18	7/12/2012 05:25:15	1420	710
19	7/12/2012 19:36:23	1241	621

Appendix E: Results verification and sensitivity analysis

In chapter 3.4 the verification and sensitivity analysis is described. Next to the extensive hypothesis testing to verify whether the model is working properly on the tested elements, also some extensive numerical testing is executed. The results of these tests are described shortly in the report, but are presented in more detail in this appendix.

Verification – distribution of containers

In the simulation model a predefined distribution of container loads (0-100% with intervals of 10%) is given. The question is whether the model returns the predefined percentages after running the simulation. In other words: if for example 15% of the containers should have a container load of 50%, is this percentage also shown by the simulation model after handling a certain amount of containers? For this a test run is done for 10,000 containers. A new process is created to count the containers based on their loads. The results for this test, presented in Table 19, show a pretty accurate similarity between the input percentages of the data and the output percentages of the simulation run. Only for the 0%, 20% and 50% container loads, the difference is bigger than 0.2%. The biggest difference is however not bigger than 0.6%. The deviations are not significant, which means that the model is working correctly on this point.

Table 19: Validation for distribution of containers per container load

Container load	Percentage (data)	Percentage (model)	Difference
0%	12.5%	12.1%	- 0.4%
20%	32.0%	32.5%	+0.5%
30%	11.1%	11.1%	0.0%
40%	11.4%	11.3%	- 0.1%
50%	13.6%	14.2%	+0.6%
60%	13.6%	13.4%	- 0.2%
70%	3.3%	3.1%	- 0.2%
80%	1.6%	1.5%	- 0.1%
90%	0.6%	0.6%	0.0%
100%	0.3%	0.3%	0.0%

Sensitivity – influence of distributions on energy peak

When the simulation model is started and a containership is berthed at the terminal, all eight quay cranes start operating immediately. However, the process times in the simulation model are hard values (and no distributions), and make no distinction between containers that are nearby the quay or on the other side of the ship. Therefore is looked at the sensitivity of the energy peak, based on changed process times for the two spreader moving to ship processes. A random uniform distribution is used with the standard process time as average and the lower value -25% and upper value +25%. For example: a process time of 4 seconds is converted (in Simio language) to "Random.Uniform(3,4,5)". The result is that there is no significant difference in peak demand when the process times for the spreader to ship process are changed: 18,422 kW (standard) versus 18,561 kW (changed). This relative difference of 0.75% would imply a cost difference of €3,700[16] on a yearly base.

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[16] $(18{,}561 - 18{,}422) * €2{,}2445 * 12 = €3{,}743$, see paragraph 1.3 for a more elaborate discussion on the cost calculation of energy peaks.

Appendix F: Results simulation model

Table 20: Detailed results for limiting number of simultaneously lifting quay cranes at 8-crane terminal

Number of quay cranes	Number of lifting quay cranes	PeakDemand	Half width peak demand	Peak reduction (%)	PeakCosts (€/year)	Total savings (€/year)	Handling time (hours/week)	Handling time (hours/year)	Extra handling time	Extra handling time (sec/year)	Total savings per second (€/sec.)	Delayed containers (%)	average waiting time (sec./container)
8	**8**	**19230**	**467.6**	-	**€ 517,941**	-	**30.9**	**2460.0**	-	-	-	**0.0%**	**0.0**
8	7	17828	362.0	7.3%	€ 480,166	€ 37,775	31.0	2462.0	0.08%	7,315	€ 5.16	0.2%	7.2
8	6	15598	514.1	18.9%	€ 420,123	€ 97,818	31.0	2464.3	0.18%	15,672	€ 6.24	0.6%	5.4
8	5	13651	424.0	29.0%	€ 367,676	€ 150,265	31.0	2466.7	0.27%	24,305	€ 6.18	1.6%	3.9
8	4	11988	302.0	37.7%	€ 322,878	€ 195,063	31.0	2469.1	0.37%	32,938	€ 5.92	5.7%	2.9
8	3	9239	218.1	52.0%	€ 248,847	€ 269,094	31.3	2488.7	1.17%	103,446	€ 2.60	17.8%	2.9
8	2	6689	114.7	65.2%	€ 180,168	€ 337,773	32.7	2604.4	5.87%	520,095	€ 0.65	59.4%	4.4
8	1	4102	27.1	78.7%	€ 110,480	€ 407,461	57.3	4561.6	85.43%	7,565,969	€ 0.05	99.8%	37.6

Table 21: Detailed results for limiting number of simultaneously lifting quay cranes at 6-crane terminal

Number of quay cranes	Number of lifting quay cranes	PeakDemand	Half width peak demand	Peak reduction (%)	PeakCosts (€/year)	Total savings (€/year)	Handling time (hours/week)	Handling time (hours/year)	Extra handling time	Extra handling time (sec/year)	Total savings per second (€/sec.)	Delayed containers (%)	average waiting time (sec./container)
6	**6**	**14940**	**312,3**	-	**€ 402.397**	-	**41,2**	**3277,4**	-	-	-	**0,0%**	**0,0**
6	5	13280	296,5	11,1%	€ 357.687	€ 44.710	41,2	3278,2	0,03%	3049	€ 14,67	0,3%	5,5
6	4	11134	165,1	25,5%	€ 299.883	€ 102.514	41,2	3279,6	0,07%	7839	€ 13,08	1,7%	3,4
6	3	9187	162,7	38,5%	€ 247.436	€ 154.961	41,4	3291,9	0,44%	52289	€ 2,96	7,2%	2,8
6	2	6552	12,4	56,1%	€ 176.475	€ 225.922	42,1	3349,1	2,19%	258119	€ 0,88	29,9%	3,3
6	1	3811	33,5	74,5%	€ 102.639	€ 299.759	57,4	4565,6	39,30%	4637439	€ 0,06	99,7%	17,0

Table 22: Detailed results for limiting maximum energy demand at 8-crane terminal

Number of quay cranes	Maximum energy demand (kW)	PeakDemand	Half width peak demand	Peak reduction (%)	PeakCosts (€/year)	Total savings (€/year)	Handling time (hours/week)	Handling time (hours/yr)	Extra handling time	Extra handling time (sec/year)	Total savings per second (€/sec.)	Delayed containers (%)	average waiting time (sec./container)
8	**Infinity**	**19,230**	**467.6**	**-**	**€ 517,941**	**-**	**30.9**	**2461.3**	**-**	**-**	**-**	**0.0%**	**0.0**
8	20,000	19,195	427.2	-0.2%	€ 517,008	€ 933	30.9	2461.3	0.0%	48	€ 19.54	0.0%	0.1
8	19,000	18,788	267.9	-2.3%	€ 506,043	€ 11,898	30.9	2461.1	0.0%	-573	-€ 20.77	0.0%	1.4
8	18,000	17,907	69.7	-6.9%	€ 482,311	€ 35,630	30.9	2461.1	0.0%	-620	-€ 57.43	0.1%	2.1
8	17,000	16,954	33.3	-11.8%	€ 456,646	€ 61,295	30.9	2459.8	-0.1%	-5,393	-€ 11.37	0.1%	2.7
8	16,000	15,972	13.8	-16.9%	€ 430,190	€ 87,751	30.9	2461.6	0.0%	1,432	€ 61.29	0.3%	3.2
8	15,000	14,983	14.7	-22.1%	€ 403,542	€ 114,399	31.0	2462.8	0.1%	5,727	€ 19.97	0.4%	3.6
8	14,000	13,991	7.5	-27.2%	€ 376,830	€ 141,111	30.9	2461.1	0.0%	-716	-€ 197.10	0.5%	3.9
8	13,000	12,990	6.3	-32.4%	€ 349,869	€ 168,072	30.9	2461.4	0.0%	668	€ 251.53	0.9%	4.0
8	12,000	11,994	5.8	-37.6%	€ 323,053	€ 194,888	31.0	2463.2	0.1%	7,105	€ 27.43	1.4%	3.7
8	11,000	10,993	6.7	-42.8%	€ 296,072	€ 221,869	31.0	2462.5	0.1%	4,534	€ 48.93	2.3%	3.6
8	10,000	9,997	3.4	-48.0%	€ 269,256	€ 248,685	31.0	2464.7	0.1%	12,362	€ 20.12	3.7%	3.5
8	9,000	8,999	1.1	-53.2%	€ 242,376	€ 275,565	31.0	2468.6	0.3%	26,584	€ 10.37	6.9%	3.4
8	8,000	7,999	0.8	-58.4%	€ 215,445	€ 302,496	31.1	2474.8	0.5%	48,635	€ 6.22	11.4%	3.6
8	7,000	6,999	1.2	-63.6%	€ 188,511	€ 329,430	31.3	2492.8	1.3%	113,402	€ 2.90	20.0%	3.8
8	6,000	5,999	0.9	-68.8%	€ 161,584	€ 356,357	31.9	2541.2	3.2%	287,800	€ 1.24	38.6%	5.1
8	5,000	4,999	0.4	-74.0%	€ 134,650	€ 383,291	35.0	2787.4	13.3%	1,174,108	€ 0.33	70.8%	9.0
8	4,000	4,000	0.0	-79.2%	€ 107,736	€ 410,205	44.7	3558.8	44.6%	3,951,111	€ 0.10	91.6%	22.0

Table 23: Detailed results for limiting maximum energy demand at 6-crane terminal

Number of quay cranes	Maximum energy demand (kW)	PeakDemand	Half width peak demand	Peak reduction (%)	PeakCosts (€/year)	Total savings (€/year)	Handling time (hours/week)	Handling time (hours/yr)	Extra handling time	Extra handling time (sec/year)	Total savings per second (€/sec.)	Delayed containers (%)	average waiting time (sec./container)
6	**Infinity**	**14,940**	**312.3**	**-**	**€ 402,401**	**-**	**41.2**	**3277.4**	**-**	**-**	**-**	**0.0%**	**0.0**
6	15,000	14,764	176.2	-1.2%	€ 397,640	€ 4,761	41.2	3277.2	0.0%	-788	-€ 6.05	0.0%	0.7
6	14,000	13,952	41.9	-6.6%	€ 375,780	€ 26,621	41.2	3278.1	0.0%	2,351	€ 11.33	0.1%	1.6
6	13,000	12,990	5.6	-13.1%	€ 349,869	€ 52,531	41.2	3277.3	0.0%	-453	-€ 115.86	0.2%	2.4
6	12,000	11,985	11.2	-19.8%	€ 322,814	€ 79,587	41.2	3277.3	0.0%	-441	-€ 180.27	0.3%	3.4
6	11,000	10,983	14.4	-26.5%	€ 295,823	€ 106,578	41.2	3277.8	0.1%	1,342	€ 79.40	0.6%	3.3
6	10,000	9,998	2.6	-33.1%	€ 269,279	€ 133,121	41.2	3278.8	0.0%	5,208	€ 25.56	1.2%	3.6
6	9,000	8,998	2.0	-39.8%	€ 242,359	€ 160,042	41.2	3280.3	0.1%	10,303	€ 15.53	2.2%	3.4
6	8,000	7,998	1.9	-46.5%	€ 215,418	€ 186,983	41.3	3283.4	0.2%	21,734	€ 8.60	4.4%	3.4
6	7,000	7,000	0.4	-53.1%	€ 188,531	€ 213,869	41.4	3292.6	0.5%	54,720	€ 3.91	8.7%	3.6
6	6,000	5,999	0.6	-59.8%	€ 161,587	€ 240,814	41.7	3314.6	1.1%	133,853	€ 1.80	17.4%	3.9
6	5,000	4,999	0.6	-66.5%	€ 134,643	€ 267,758	42.4	3370.4	2.8%	334,955	€ 0.80	33.8%	5.3
6	4,000	3,999	0.4	-73.2%	€ 107,716	€ 294,685	46.7	3718.1	13.4%	1,586,525	€ 0.19	70.9%	8.8

Appendix G: Paper

On the next pages, the paper can be found that is written as part of the master thesis project. The paper is proposed to be published in Transport Policy, *'an international refereed journal aimed at bridging the gap between theory and practice in transport'* (Elsevier, 2015). For this purpose the lay-out of the paper is adapted to the standards of Transport Policy.

Opportunities for peak shaving energy demand of ship to shore quay cranes at container terminals

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Abstract

This paper presents the results of both a qualitative and quantitative study towards the possibilities for peak shaving the energy demand of ship-to-shore cranes at container terminals. The objective of this paper is to present an energy consumption model that visualises the energy demand of ship-to-shore cranes and to show the possibilities for reducing the peak demand of ship-to-shore cranes by implementing rules of operation (i.e. changes to the business operational procedures). The results show that the peak demand (and peak related costs) can be reduced by 50%, while the handling time of containerships increases by less than half a minute per hour handling time. This can be achieved by reducing the maximum energy demand of all operating ship-to-shore cranes or by limiting the maximum number of simultaneously lifting ship-to-shore cranes. By implementing (one of) these rules of operation an intermediate container with 6-8 ship-to-shore (STS) cranes is able to save up to €250,000 per year, which is about 48% of the total peak-related energy costs.

Keywords: Peak shaving; Container terminals; Electricity demand; Energy consumption; Ship-to-shore cranes

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1 Introduction

1.1 Growth in containerised transport

The worldwide throughput of containers is growing continuously. The standardised size of the container (in 20ft. and 40ft. equivalents) makes it a suitable mean for transporting all kinds of products, ranging from multimedia and building material to clothing and shoes. Even temperature-sensitive goods like flowers, fruits and vegetables can be transported easily by temperature-controlled containers, known as reefers. The share of containerised transport in seaborne trade increased from 2.75% (1980) to 16.5% (2013), while the total seaborne trade increased with 158% over this period (UNCTAD, 2013). The annual worldwide transport of containers increased from 28.7 million TEU in 1990 to 153 million TEU in 2010 (World Shipping Council, 2011). The 20-years average growth percentage of the container market shows a remarkable 7.8% (Clarksons, 2015).

An important development that facilitates the growing container market is the growing capacities of containerships. Where the largest containership in 1980 had a capacity of 3,000 TEU, the biggest containerships operating in 2015 have a capacity of almost 19,224 TEU (Lloyd's List, 2015).

The growing size of containerships influences the container terminals' operations, since the number of containers per containership also increased due to this development. Container carriers demand container terminals to handle their ships as fast as possible to continue their journey to the next port. This higher productivity is achieved by more automated terminal processes (Grunow, Günther, & Lehmann, 2005) and by deploying more terminal equipment simultaneously. However, with more and more simultaneously operating ship-to-shore cranes, the energy demand (kW/s) is increasing. This also increases the highest observed peak demand, leading to a higher energy bill and therefore higher handling costs.

The peak demand of container terminals is responsible for about 25-30% of the monthly energy bill (ABB, 2014) (Stedin, 2014). The main reason is that the highest observed peak demand is charged for the next twelve months. To illustrate this: if the highest peak in January is 12,000kW, the terminal is charged 12,000 times the monthly tariff for the rest of the year. However, when the highest peak in March is 14,000kW, the terminal is charged 14,000 times the monthly tariff until March the year after. A lower peak demand might save container terminals at least tens of thousands euros per year. It is therefore very important to investigate the possibilities to reduce this peak demand.

The research objective is therefore to investigate the possibilities for peak shaving the electricity demand at container terminals by applying new rules of operation for electricity consuming terminal processes, while meanwhile monitoring the consequences for the handling speed of containerships.

This paper presents the results of this research by discussing the terminal operations and volatility of the energy demand of STS cranes in chapter 1. The applied methodology and relevance are presented in chapter 2. Chapter 3 presents the energy consumption model, which forms the basis for the developed simulation model. The simulation model is presented in chapter 4 and the results of the simulation study are discussed in chapter 5. The implications of these results and conclusions of the study are discussed in chapter 5 and 6.

1.2 Operations ship-to-shore cranes

After a containership has berthed at the sea-side of a terminal, the ship-to-shore cranes start unloading the incoming containers based on the unloading plan. Ship-to-shore cranes can use a normal spreader, enabling them to handle one container at a time or more advanced spreaders (e.g. the twin-lift and tandem-lift) to handle multiple containers at the same time (Stahlbock & Voß, 2008). The Super Post Panamax ship-to-shore cranes, the current standard for unloading the largest containerships, are able to make approximately 32 lifts per crane per hour (APM Terminals, 2014). This allows a ship-to-shore crane to handle 32-64 TEU per hour with a normal spreader and up to 128 TEU per hour with a tandem lift spreader.

The handling capacity of a container terminal is highly dependent on the number of ship-to-shore cranes and their capacity, since the cranes determine the handling time for a ship as well as the throughput of containers to the stacking process (Eugen, Şerban, Augustin, & Ştefan, 2014).

During the (un)loading of a containership, two criteria are important: the ship's stability and number of unproductive moves (Imai, Sasaki, Nishimura, & Papadimitriou, 2006). While (un)loading, the ship's stability changes due to the continuously changing container load. Because containerships visit several container terminals, each of them unloading containers from and loading containers to the ship, not all containers which have to be unloaded are positioned on top of the ship's stacks. The ships therefore have to be loaded in an efficient way, allowing the next container terminal to unload the containership with a minimum of unproductive moves.

These two criteria are often in conflict, because the most efficient loading (regarding the minimisation of unproductive moves) might not also be in line with the most efficient loading regarding the ship's stability. This makes the stowage very complex (Bortfeldt & Gehring, 2001) (Steenken, Voß, & Stahlbock, 2004) (Dekker, Voogd, & Van Asperen, 2006), especially because the stowage plans have to be aligned over all different ports that have to (un)load the ship (Wilson & Roach, 2000).

1.3 Volatility of energy demand

The ship-to-shore cranes are connected to the electricity network. For all quay crane processes (moving of crane and spreader, crane lighting and auxiliary processes) electricity is supplied by the netwerk. The vertical movements have the most volatile energy demand, showing high peaks for hoisting spreader of the crane and low falls for lowering the spreader, as can be seen in Figure 1 (MSC Terminal Valencia, 2009). The gantry (horizontal) movements and auxiliary energy consumption show a less volatile character.

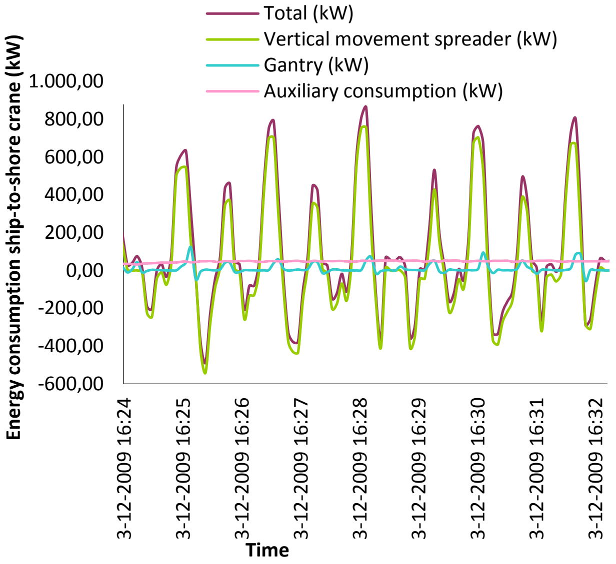

Figure 1: Detailed energy consumption of quay crane (MSC Terminal Valencia, 2009)

In Figure 2 the total energy consumption for one ship-to-shore crane is visualised. In total two peaks can be identified for handling a container. The first peak for lifting a spreader and container above the ship and the second peak for lifting the spreader after the container is positioned on the terminal. When all ship-to-shore cranes on a terminal are lifting at the same moment, the potential peak demand is very high. This supports the importance of the first paragraph to visualise the peak demand of a terminal while handling a containership and to investigate the opportunities to reduce the peak demand.

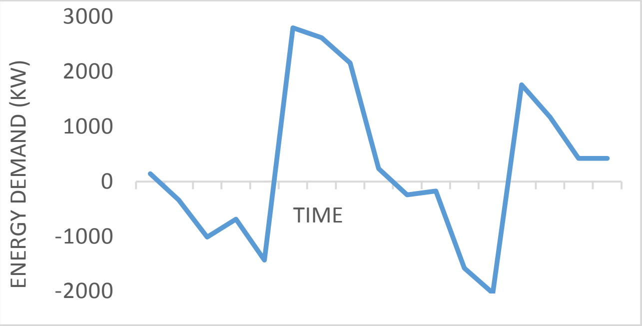

Figure 2: Energy consumption for handling one container (ABB, 2014)

1.4 Challenge for container terminals

The growing need for container terminals to handle containerships as fast as possible leads to more automatisation and more simultaneously operating ship-to-shore cranes, leading to high peaks in electricity demand. Because an observed peak demand is charged for the next twelve months, the highest peak is responsible for nearly 25-30% of the total electricity costs. This implies that higher handling speeds of containerships result in more peak related energy costs, leading to higher handling costs. Because container carriers request both higher handling speeds and lower handling costs, terminals are confronted with a dilemma. The challenge is therefore to find opportunities to reduce the peak related costs without reducing the handling speed too much.

2 Research and methodology

2.1 Research objective

The objective of the research is to investigate the opportunities for peak shaving the electricity demand, while monitoring the consequences for the handling speed of containerships. Peak shaving implies the lowering of the highest observed peak in energy demand to reduce the energy related costs. This enables container terminals to lower the handling costs of containerships, giving them a better competitive position. Another advantage of peak shaving is that the energy demand of terminals is more stable, which is especially important for container terminals in countries where grid operators cannot prepare the energy system for unexpected high energy peaks. The handling time for containerships needs to be monitored, because extra handling time might affect the terminals' competitive position. The main research question that is addressed in this research is:

"What are the possibilities for reducing the peak demand of electricity consuming terminal equipment (peak shaving) in order to reduce the electricity related energy costs?"

The hypothesis is that by implementing different rules of operation (i.e. process improvements), like limiting the number of lifting cranes of the maximum allowed energy demand, terminals are able to reduce the height of peaks, which reduces the energy-related costs.

2.2 Relevance

2.2.1 Scientific relevance

Previous research towards the energy consumption of container terminals (Geerlings & Van Duin, 2011) (Van der Voet, 2008) does not provide in visualising the peak demand of container terminals or ship-to-shore cranes. The research has two contributions to science.

1. The first scientific contribution is to develop an energy consumption model that is able to show the energy demand over time (in kW/s). Over the last years many studies have been executed towards the energy efficiency of container terminals. The models that are presented in these studies try to describe the total energy consumption over a given time interval (mostly in kWh per year). However, for visualising the peak demand of container terminals, and in particular the ship-to-shore cranes, a more advanced model needs to be developed. This consumption model can also be applied to visualise the energy demand of other types of cranes in different industries.
2. The second contribution is to present rules of operation that contribute to the reduction of peak demand at container terminals and to test these rules of operation by executing a case-study to show the opportunities for peak shaving the energy demand of ship-to-shore cranes.

2.2.2 Business relevance

The growth of containerships is increasing continuously, into the newest generation which is able to carry almost 20,000 TEU. Container terminals feel a high pressure to handle ships as fast as possible against a low price, to improve their competitive position. However, when more and more ship-to-shore cranes are simultaneously executing a lifting movement, the peak demand and energy-related costs increase. For an intermediate container terminal with eight ship-to-shore quay cranes, the peak related costs can count up to 20-30% of the total energy costs. The energy consumption model and developed rules of operation show the opportunities for container terminals to reduce these peak related costs, while monitoring the consequences for the handling time.

This can save a terminals at least tens of thousands euros per year.

2.3 Methodology

The research is executed in three different parts:

1. At first an extensive literature review is executed towards the container market and in particular the ship-to-shore crane operations. This leads to a better understanding of the problem and shows the importance to reduce the peak demand of ship-to-shore cranes;
2. Based on the acquainted knowledge an energy consumption model is developed by introducing a conceptual model and a final consumption model (mathematical formula).
3. The conceptual model is applied for a container terminal, so rules of operation can be tested quantitatively on their ability to reduce the peak demand. The simulation model is developed in a discrete-event environment, with the Simio software package (Simio LLC, 2015). The discrete modelling approach enables the modeller to model the containers as passive objects with a predefined behaviour and to visualise the energy demand per second, as time is continuing based on the occurrence of events. Other environments, like system dynamics or agent-based modelling do not facilitate in all of these aspects.
   The discrete environment has been applied in earlier research, for example to model the rail operations (Caballini, Pasquale, Sacone, & Siri, 2014), the time duration of handling activities (Cartenì & De Luca, 2011), to model and test several container stacking algorithms (Van Asperen, Borgman, & Dekker, 2010) and to model the container flows within container terminals (Alessandri, Cervellera, Cuneo, Gaggero, & Soncin, 2008) (Alessandri, Sacone, & Siri, 2007).

3 Energy consumption model

3.1 Conceptual model

As discussed earlier, the energy consumption of ship-to-shore cranes is highly dependent on the different movements that are made by the crane. In total six different general movements can be distinguished:

1. Moving spreader from quay to ship;
2. Lowering spreader at ship side;
3. Hoisting spreader at ship side;
4. Gantry (i.e. horizontal) movement from ship to shore;
5. Lowering spreader at quay side;
6. Hoisting spreader at quay side.

Each of these movements has its own energy consumption specifications (see Figure 1 and Figure 2 in §1.3). Next to these different movements, the auxiliary energy consumption is also important to include. The auxiliary consumption is a fixed energy demand per hour, needed for keeping the pressure on the crane and for equipment in the cabin and engine room. The auxiliary consumption is rather constant over time because the quay cranes are not turned off while in idle or off-shift state.

The conceptual model, visualised in Figure 3, is built on the idea of different energy specifications per type of movement and state (since the auxiliary energy consumption is also consumed in idle state). For all ship-to-shore cranes need to be determined at which moment in time a movement is executed. In that case the energy consumption (kW/s) is added to the current energy consumption. The auxiliary energy consumption per ship-to-shore crane is multiplied with the number of cranes and also added to the energy consumption, resulting in the total energy consumption for all ship-to-shore cranes. When doing this every second, the energy consumption can be visualised over time enabling the identification of peaks in energy demand.

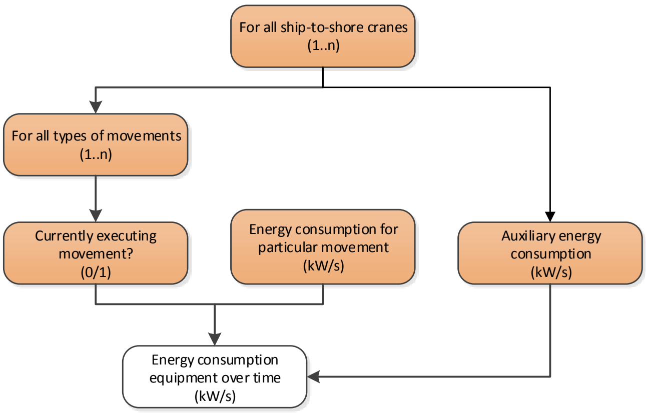

Figure 3: Conceptual model for visualizing the energy demand (kW/s)

3.2 Energy consumption model

The final energy consumption model is the mathematical representation of the conceptual model that is presented by Figure 3 in paragraph 3.1. As is shown in equation 01, the energy consumption is obtained by multiplying – for every ship-to-shore crane separately – the energy consumption specifications for the movement that is currently executed and by adding the auxiliary energy consumption.

Energy consumption container terminal per second (equation 01):

$$\sum_{h=1}^{H=4}\left(\sum_{i=1}^{I=4} m_{ih} * e_{ihl}\right) + a_h$$

Where h = type of terminal equipment

H = number of all terminal equipment:

1= quay cranes, 2= (automated) stacking cranes

3= rail cranes, 4= (barge cranes)

i = type of movement

I = number of all movements:

1= movement over terminal, 2= horizontal movement of spreader, 3= hoisting spreader, 4= lowering spreader

m_{ih} = executing particular type of movement for corresponding type of equipment? (binary: 0 if negative, 1 if positive)

e_{ihl} = energy consumption for particular type of movement, particular type of equipment and container load (kW/s)

a_h = auxiliary energy consumption for particular type of terminal equipment

Where h = type of terminal equipment

H = number of all terminal equipment

i = type of movement

I = number of all movements

m_{ih} = executing particular type of movement for corresponding type of equipment? (binary: 0 if negative, 1 if positive)

e_{ihl} = energy consumption for particular type of movement, particular type of equipment and container load (kW/s)

a_h = auxiliary energy consumption for particular type of equipment

When applying this energy consumption model over a longer period in time, the time aspect need to be added to the formula. Equation 02 shows the mathematical representation that can be used to visualise the energy demand of ship-to-shore cranes over time.

Energy consumption container terminal per second for (T-T$_0$) (equation 02):

$$\int_{t=0}^{T}\left(\sum_{h=1}^{H=4}\left(\sum_{i=1}^{I=4} m_{ih} * e_{ihl}\right) + a_h\right)dt$$

Where $t = 0$ = starting time for measuring energy consumption

T = final time for measuring energy consumption

The energy consumption model is not only suitable for visualising the energy demand of ship-to-shore cranes, but can also be used for other crane operations at container terminals (e.g. Automated Stacking Cranes and rail cranes), but even in different type of industries where cranes are used (e.g. factories or building sites).

4 Application of consumption model

4.1 Development of simulation model

As described in paragraph 2.3, a discrete-event simulation model is constructed to apply the consumption model that is presented in chapter 3. When a containership arrives and is berthed, the terminal's quay cranes are able to start the handling of containers immediately. The quay cranes take the containers through the earlier presented six movements.

The model is able to generate the following relevant output:

- energy consumption per second (kW/s);
- handling time for containers (seconds);
- number of active quay cranes;
- number of lifting quay cranes;
- number of containers that were ceased and their average ceasing time (due to limitations imposed by the rules of operation).

In Figure 4 a 3D-view of the simulation model is given. Here eight quay cranes are transporting the containers (red triangles) through the different (sub)movements. The results of the simulation model are verified with real data and by expert opinion (ABB, 2014).

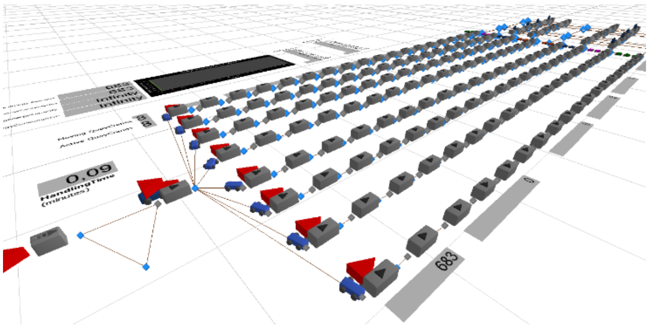

Figure 4: Screen view of simulation model

4.2 Rules of operation

The rules of operation can that are implemented need to be seen as process improvements to reduce the peak demand for ship-to-shore cranes. In total two rules of operation are implemented in the simulation model to test their impact on the peak demand and handling time:

1. **Restrict number of lifting quay cranes**
   The first rule of operation restricts the number of simultaneously lifting quay cranes, since the lifting movements are the most energy-intensive (see paragraph 1.3). When for example maximal four of the eight ship-to-shore cranes are allowed to lift simultaneously, some cranes may need to stop their operations temporarily, waiting until one of the other cranes finishes its lifting movement.
2. **Restrict maximal energy demand**
   The second rule of operations restricts the maximal energy demand per second. Before starting a new movement, every ship-to-shore crane requests the energy that it is expecting to consume (dependent on the type of movement and container load). Based on this expected consumption, the simulation model looks whether this demand is available. If not, the crane is asked to pause, until there is enough demand left to start the movement.

4.3 Validation simulation model

The rules of operation are applied for two types of container terminals (6 and 8 ship-to-shore cranes) and a yearly throughput of 1.6 million TEU. The base scenario of the simulation model is executed with the standard specifications of the container terminal. This means that all eight quay cranes are handling containers, without any restrictions towards the number of simultaneously lifting quay cranes or maximum energy demand per second. The base scenario is run with ten replications (more than the minimum desired eight replications, as calculated in the last sub-paragraph). As discussed earlier, the time span is one week. During this week 19 containerships arrive with a total of 20,114 TEU. Without implementing one of the rules of operation, the peak demand is 19,230W and peak related energy costs are €518,000, based on the tariff of Dutch grid operator Stedin (2014). The average maximum energy demand of all replications is 19,177kW, with a minimum of 18,063kW and a maximum of 20,004kW. The corresponding half width is 364.4kW. The handling time of all containers is 1,857 minutes, which is 31.0 hours.

The model is validated on three important aspects: the container load, observed peak demand and handling time. All three aspects are discussed below.

Container load

Each container load (0% - 100%) has its own pre-defined energy specifications (kW/s). Multiplied by the operation times per sub-movement, the total energy consumption for a container can be determined and compared with real data. The result is that the maximum difference in energy consumption is 0.9%. For most container loads the difference is not larger than 0.2%. Because the different container loads are not appearing in the same proportion, the difference is multiplied with their appearance distribution (container mix). The results is a weighted difference of 0.26% (see Table 1 on next page), which might be considered not significant to the energy consumption results. The influence on the energy peak is however difficult to calculate, because that depends on the current container mix, which is changing continuously in the simulation model.

Table 1: Weighted difference for difference in energy demand

Container load	Container mix	Difference	Weighted difference
0%	12.5%	0.00%	0.00%
20%	32.0%	0.20%	0.06%
30%	11.1%	0.35%	0.04%
40%	11.4%	0.16%	0.02%
50%	13.6%	0.00%	0.00%
60%	13.6%	0.90%	0.12%
70%	3.3%	0.42%	0.01%
80%	1.6%	0.21%	0.00%
90%	0.6%	0.00%	0.00%
100%	0.3%	0.00%	0.00%
		Total weighted average	**0.26%**

Peak demand

When comparing the peak demand of the simulation (base scenario with eight lifting quay cranes and no restriction towards the maximum energy demand per second), the peak demand lies around 20,000kW. This is consistent with data that of a terminal with eight quay cranes (ABB, 2014), which validates the outcome of the simulation model on this aspect.

Handling time

The total run time for the base scenario is 171.0 hours (one week plus three hours extra run time). The quay cranes are operating 18.0% of the time (half width 0.5%), which is 30.8 hours. In this time frame 10,057 containers are handled. Based on the fact that eight quay cranes are operating, resulting in a handling time of 88.1 seconds/container.

The theoretical (weighted) handling time of a container (based on the appearance of each container load) is 91.4 seconds/container, a difference of 3.3 seconds (3.6%). This difference could be explained by random distribution of process times for engaging the container in the simulation model, while the theoretical handling time makes use of standard process times instead of a distribution.

5 Results

5.1 Results for limiting number of lifting quay cranes

When reducing the number of lifting ship-to-shore cranes, the peak demand is decreasing, as shown in Figure 5. Striking is that the handling time is not increasing in the same proportion. A reduction to four lifting cranes leads to an extra handling time of 0.37% (i.e. less than half a minute per hour). The handling time is not impacted that much because of the fact that the maximum peak demand with eight cranes (around 19,000kW) is only occurring shortly. As shown by Figure 6, for a peak demand of 19,000kW, an energy demand of more than 9,000kW is only occurring 1.1% of the time. Most of the times the energy demand is lower than 9,000kW.

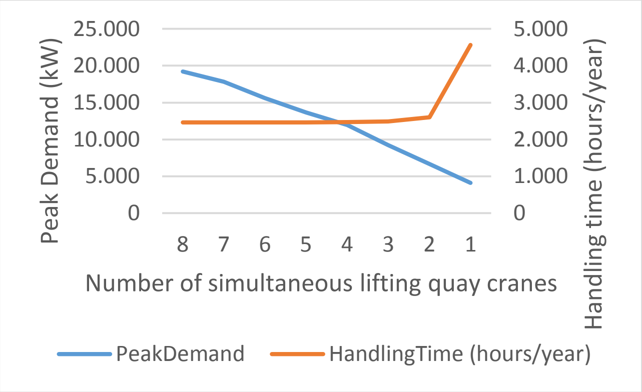

Figure 5: Relation peak demand and handling time for restricting number of lifting cranes

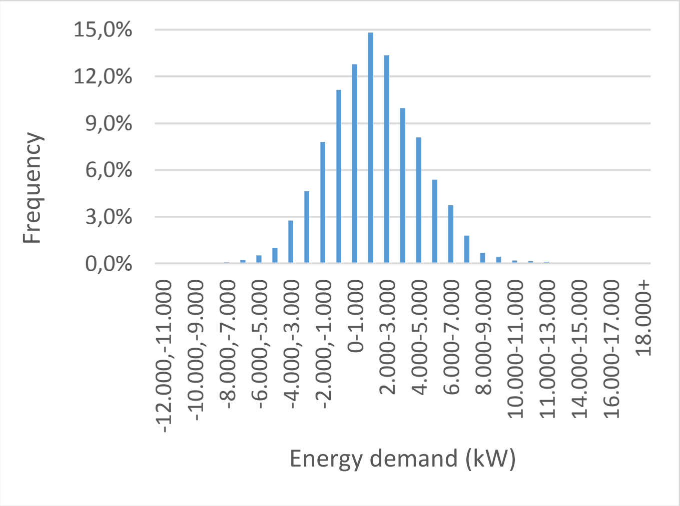

Figure 6: Frequency (per 0.1s) per energy demand interval

As can be concluded from Figure 5, restricting the number of simultaneously lifting quay cranes has a positive influence on the reduction of the peak demand. When looking to the impact on the cost savings on the one hand and handling time on the other hand, one can look to the most cost-effective scenario (i.e. yearly savings per extra second handling time) and the total cost reduction against a particular extra handling time.

The optimal cost-effective implementation is to reduce the number of lifting quay cranes to 6 (8-crane terminal) or 5 (6-crane terminal) as can be seen in Figure 7. In these cases the savings per extra second handling time are higher than for other scenarios.

When looking to the total yearly savings against an extra handling time of less than 1.0%, the number of quay cranes can be limited even more. In case of an 8-crane terminal this could result in a reduction to 4 lifting cranes. This saves €195,000, which is 39% of the peak related costs. For a 6-crane terminal this would results in a reduction to 3 lifting cranes, which saves €155,000 (reducing the total peak demand costs by 38%).

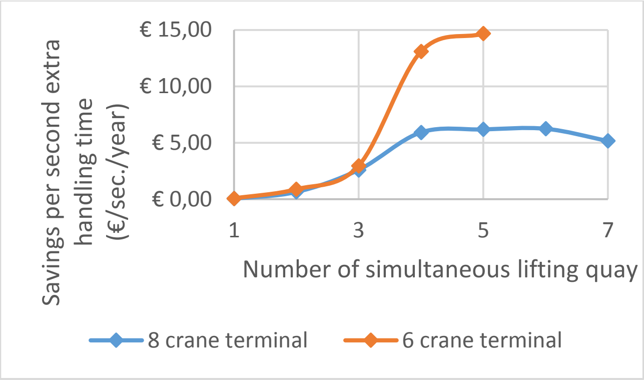

Figure 7: Savings per extra second handling time when restricting number of lifting cranes

5.2 Results for limiting maximum energy demand

For limiting the maximum energy demand per second, the relation between the maximum allowed energy demand and handling time (see Figure 8) is comparable with the limitation where the number of simultaneously lifting ship-to-shore cranes is limited. The maximum energy demand can be reduced by almost 50% (from 19,000kW to 9,000kW) while the handling time increases by 0.1%. Only by restricting the energy demand too much (to less than 6,000kW) the handling time increases with 3-45%.

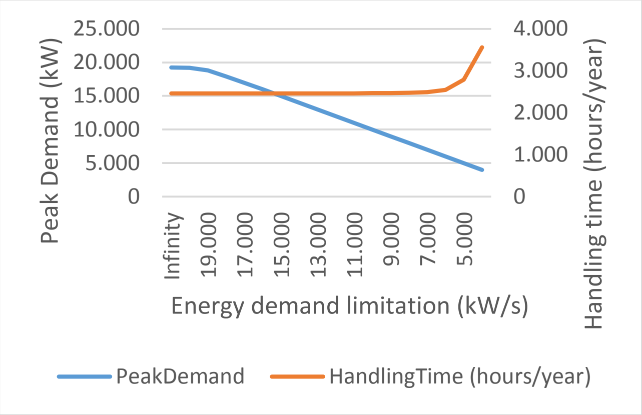

Figure 8: Relation peak demand and handling time for restricting maximum energy demand

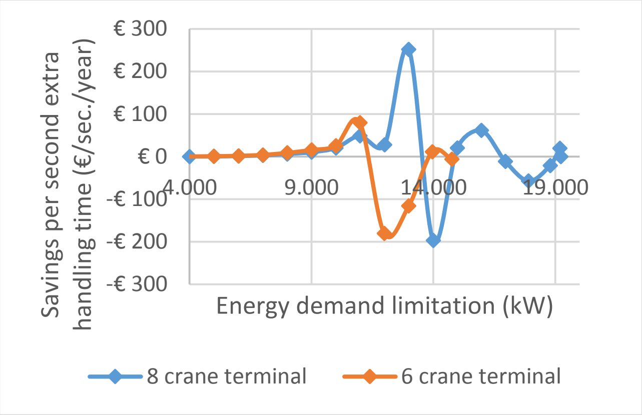

Figure 9: Savings per extra second handling time when restricting maximum energy demand

A restriction to the maximum allowed energy demand has a positive influence on the reduction of the terminals' peak demand. The influence on the handling time is only minimal when reducing the allowed energy demand by approximately less than 50%, while it enables the container terminals to see its peak related energy costs reduced hugely.

When the total savings per year are divided by the extra handling time that is needed to handle all containers on a yearly base, the savings per second are obtained, as shown by Figure 9. For the 8-crane terminal there is a clear optimum when reducing the maximum demand to 14,000kW. In this case the savings are €141,000 per year, while the handling time is 0.01% faster. This results in a negative saving[1] of €197.10 per second. Restricting the energy demand to 17,000kW, 18,000kW or 19,000kW results also in a negative saving. However, in these cases the total savings are only €12,000 to €61,000. Restricting the energy demand to 13,000kW gives a saving of €251.53 per second, which the absolutely seen the highest saving.

For the 6-crane terminal the highest (negative) saving per second is obtained by reducing the maximum energy demand to 12,000kW (-€180.27 per second) or 13,000kW (-€115.86 per second), saving the terminal resp. €80,000 or €53,000 per year. The highest positive value (meaning a saving against extra handling time) is achieved by reducing the energy demand to 11,000kW. This saves €79.40 per second against an extra handling time of 0.01% and a total cost saving of €107,000.

5.3 *Analysis of results*

The outcomes presented in the first two paragraphs of this chapter show a clear outcome: it is possible to reduce the peak demand, saving up to €250,000 per year against a little extra handling time (in some scenarios without extra handling time). The bigger the restriction of the rules of operation, the larger the effect on the operations, visualised by the number of temporarily delayed containers. However, since more and more container terminals are operating automatically, this can be integrated in the terminals' software. The delay of containers should be no problem when implementing one of the rules of operation.

Regarding total cost savings, the optimal solution is to reduce the maximum energy demand per second by 50% of the original highest observed energy demand. By doing this, €160,000 - €249,000 (40% - 48% of peak related costs) can be saved annually. The impact on terminal operations are small, since the extra handling time is only 0.1% and the number of temporarily delayed containers is 2.2% - 3.7%. The savings per second are €15.53 - €20.12.

When the savings per second extra handling time are considered to be more important than the total annual savings (for example to compensate container carriers, see next paragraph), the maximum energy demand can be reduced by 30% - 35% (13,000 kW/s - 14,000kW/s) for an 8-crane terminal or by 5% - 15% for a 6-crane terminal (12,000 kW/s - 13,000kW/s). Because the handling time is hardly affected, the extra savings per second are very high, especially because some of these scenarios showed a small quicker handling time against a restricted energy demand.

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[1] The negative cost saving per second is actually a positive result, since the handling time for this scenario is lower compared to the standard situation, which means that the cost savings (positive result) are divided by a negative extra handling time (i.e. less handling time).

When reducing the number of lifting quay cranes by 50%, the peak related costs are reduced by approximately 40% (saving up to €195,000 per year). The extra handling time is only 0.37% - 0.44% (less than half a minute per hour handling time) against a saving of €2.96 - €5.92 per second extra handling time. By reducing the number of simultaneously lifting quay cranes by less than 50%, the total savings are less, while the savings per second are not increasing. By reducing the number of lifting quay cranes by more than 50% the peak demand decreases even further, but the handling time increases drastically. The most optimal solution would therefore be to reduce the number of simultaneously lifting quay cranes by 50%.

6 Implications of results

6.1 Extra handling time

Extra waiting time for containerships is something that is watched critically by the container carriers. Despite the critical attitude of cargo carriers towards waiting time in ports, the adaption of containerships' cruising speeds (also known as slow steaming) is no issue. For container carriers, their biggest costs are fuel. These costs might be reduced by adapting the ship speed: a reduction to 80% saves 60% fuel costs, while a reduction to 60% saves 90% of the fuel costs (Wärtsilä, 2010). A market survey showed that 75% of the surveyed liners and carriers apply slow steaming in order to save bunker costs (Seatrade Global, 2014). Since the fuel costs are that high, container carriers are operating more efficient when sailing at lower speeds. In this regard the extra travel time is compensated by fuel savings.

6.2 Costs containership

For handling 2,000 TEU of a containership (loading and unloading) a terminal needs approximately 18 hours using only three quay cranes. When extra handling time is needed, the question is whether container carriers are willing to accept this without any form of compensation. If terminal operations take more time than agreed in advance, carriers are compensated, known as demurrage (Haugen Consulting, 2015). When a ship requires less time than agreed on forehand, the terminal can request a bonus for quicker handling, the so called despatch. This shows that compensation is quite regular in the shipping business.

The question is therefore whether container terminals are able to compensate container carriers to a certain extent. To answer this question, first the costs for a containership need to be determined. To determine the annual costs for a containership, AECOM made a report for the North Carolina Department of Transportation (2012). They pointed out three cost aspects: the investment costs for a containership, labour costs and fuel costs. The purchase of a containership of 15,000 TEU (Emma Maersk class) costs around 127 million euros (Maersk, 2006). When dividing these costs over a lifespan of 30 years and an annual discount rate of 6%, this is ±9 million euros per year. Labour costs can be estimated at 1.2 million euros (AECOM, 2012). Fuel costs can be neglected, since extra handling time will not lead to extra fuel consumption.

Table 2: Cost containership per year, hour and second

Type of cost	Costs
Investment costs	€ 9,000,000
Labour costs	€ 1,200,000
Total per year	**€ 10,200,000**
Total per hour	**€ 1,164**
Total per second	**€ 0.32**

Since a peak reduction of 50% saves a container terminal at least €2.96-5.92 per second, this leaves room to compensate the carriers for the extra handling time. This could result in a win-win situation: container terminals saving costs by reducing their peak demand and carriers reducing their handling costs due to the compensation.

7 Conclusions

The objective of the research was to investigate the opportunities for lowering the peak demand of ship-to-shore crane operations at container terminals. When trying to reduce the peak demand of container terminals by implementing new rules of operation (i.e. reducing the number of simultaneously lifting cranes or by limiting the maximum energy demand), it is shown that the peak can be reduced by 50% while impacting the handling time less than half a minute per hour. A cost reduction of 50% saves a container terminal with eight quay cranes and a throughput of 1.6 million TEU up to €275,000 per year.

Despite the positive effect of cost savings, the reduction of peak demand has consequences for the handling time. In most scenarios (dependent on how much the number of simultaneously lifting cranes and energy demand per second is limited) the extra handling time would be less than half a minute per hour. The question is whether container carriers are willing to accept extra handling time. Container terminals need to be prepared to negotiate with container carriers about some sort of compensation. This can be financially, but also regarding extra service (e.g. free electricity power for ships while berthed) or sustainability agreements. Despite the cost allocation, the research showed that container terminals can reduce their peak related energy costs by managing the energy consumption in a smarter way.

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