# Peak Shaving the Electrical Power Demand of Ship-to-Shore Cranes

## Developing operational policies to maintain productivity under increasingly restrictive peak power limitations

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## Developing operational policies to maintain productivity under increasingly restrictive peak power limitations

by

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in partial fulfilment of the requirements of the degree of

**Master of Science**
in Mechanical Engineering

at the Department Maritime and Transport Technology of Faculty Mechanical, Maritime and Materials Engineering of Delft University of Technology
to be defended publicly on Friday August 25, at 14:00

| | | |
|---|---|---|
| Student number: | 4900316 | |
| MSc track: | Multi-Machine Engineering | |
| Report number: | 2023.MME.8839 | |
| Thesis committee: | Dr. F. Schulte | Daily supervisor, TU Delft |
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| Project duration | February, 2023 - July, 2023 | |

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# Preface

I am delighted to present this master's thesis, which marks the completion of my master's degree in Mechanical Engineering at Delft University of Technology. Over the past six months, I have devoted my time to exploring the topic of peak shaving the electrical power of ship-to-shore cranes. Through rigorous research and analysis, I have uncovered insights that make a valuable contribution to the existing literature in this field.

Throughout the process of conducting this research, I have been fortunate to receive guidance and support from various individuals. I would like to express my deepest gratitude to Frederik, my supervisor from TU Delft, for his valuable contributions. His expertise, encouragement, and willingness to actively participate in discussions and provide insightful answers to my questions have played a vital role in shaping this thesis. I would also like to extend my sincere appreciation to my supervisor from Portwise, Pim, for his support and assistance throughout this journey. His industry knowledge, practical insights, and critical feedback have played an indispensable role in the development and execution of this research. Lastly, I would also like to express my gratitude to Jasper for the fruitful brainstorming sessions.

It is my hope that this thesis provides readers with valuable insights into peak shaving strategies for ship-to-shore cranes and inspires further exploration and innovation in the field. May this work contribute to the advancement of sustainable and efficient operations in container terminals and other industries facing similar challenges.

*M.C. van Meijeren*
*Barendrecht, July 2023*

# Abstract

Electrification of numerous end-users is a worldwide trend to address climate change, according to the International Energy Agency. This trend has also reached container terminal operators. Currently most of the ship-to-shore cranes employed are electrified, leading to an increase in the required electrical power demand and to an increase in the volatility of the electrical power demand of container terminals. As a result, the contractual power demand charged by the grid operator, based on the maximum required power demand (peak power) at any moment in time, is upscaled, leading to additional costs for the container terminal operator. However, the highest required power demand values occur infrequently, leading to significant expenses for a resource that is rarely utilised. By implementing a peak shaving strategy, the peak power can be reduced, leading to a decrease in the contractual power demand related costs. Nevertheless, it is crucial to minimise the impact of the specific peak shaving strategy on the productivity of a container terminal to actually derive economic benefits from its implementation.

The aim of this study is to develop operational policies that effectively maintain productivity for a cluster of six ship-to-shore cranes under increasingly restrictive peak power limitations. A discrete event simulation approach was employed for evaluating the operational and economic impact. In total four policies were developed, two according to the 'who fits is served' approach (policy 0 and policy 1) and two according to the 'priority based' approach (policy 2 and policy 3). In the first approach the initiation of a movement only depends on the power availability, while for the second approach the initiation of a movement depends on the power availability and the urgency of the movement in terms of productivity. Moreover, for both approaches one policy allows only one kinematic profile (policy 0 and policy 2) and one policy allows varying kinematic profiles (policy 1 and policy 3). A metaheuristic was employed to find near-optimal adapted kinematic profiles.

The findings of this study suggest that the established 'priority based' approach is more effective than the 'who fits is served' approach in maintaining productivity under increasingly restrictive peak power limitations. When combined with the allowance of adapted kinematic profiles (policy 3), this strategy achieves the most cost savings. Policy 3, has been shown to reduce the contractual power demand related costs by 53% compared to the baseline scenario, which is the greatest recorded reduction of all created policies without adversely affecting the ship-to-shore cranes' productivity.

# Abbreviations

**AGLV** automated guided lift vehicle.

**CT** container terminal.

**ESS** energy storage system.

**FW** flywheel.

**GHG** greenhouse gas.

**OC** operational constraint.

**RE** regenerative energy.

**RMG** rail mounted gantry.

**STS** ship-to-shore.

**TEU** twenty-foot equivalent unit.

**UC** ultracapacitor.

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# 1. Introduction

Climate change is one of the biggest challenges facing humanity, according to the European Environment Agency [1]. Its impact encompasses a range of phenomena, including elevated temperatures, more frequent droughts and wildfires, altered rainfall patterns, melting glaciers and snow, and rising sea levels. To mitigate climate change, greenhouse gas (GHG) emissions attributed to human activities must be reduced. Electrification of numerous end-users is a worldwide trend to address climate change, according to the International Energy Agency [2]. The shift towards electrification has led to a substantial increase for power, requiring a transformation of the global power system.

The trend of electrification has also reached container terminal (CT) operators, resulting in changes in the power sources utilised by various CT equipment. This study specifically focuses on the electrification of ship-to-shore (STS) cranes. This chapter presents the research design of the study conducted. Section 1.1 provides a comprehensive problem statement that serves as the foundation for the research. Building upon the problem statement, Section 1.2 formulates the research objective, which is accompanied by the scientific relevance, business relevance, and environmental and societal relevance of the study. Section 1.3 outlines the corresponding research question. Section 1.4 delineates the research scope, highlighting specific considerations and limitations of the study. Finally, the study outline is presented in Section 1.5.

## 1.1. Problem Statement

The electricity market/system has three main parties: (1) the grid operator, (2) the consumer, and (3) the supplier. The grid operator is responsible for balancing the demand and supply and the transport capacity of the infrastructure. The consumer has a demand for electricity and the supplier supplies electricity. The grid operator allocates a specific portion of the accessible transportation capacity to every consumer, based upon their anticipated maximum required power demand (further referred as 'peak power') at any moment in the contractual year. Herewith, the grid operator makes sure that there is always enough power available for the consumer to prevent blackouts that could damage the electrical equipment. The consumer is charged by the grid operator based on the reserved transport capacity, as outlined in Section 2.3.

Recently industries are pushed by international and regional institutions to reduce their GHG emissions and become more sustainable [30]. Electrification is suggested as a promising solution to limit GHG emissions [18]. As a result, more and more equipment is being electrified and the total electricity demand increases. A conventional approach to transport the required increasing demand involves capacity addition [35]. However, grid operators prefer to make more intensive use of their grid capacity to avoid large investments. For grid operators, it is preferable that consumers reduce their peak power demand such that the reserved transport capacity for that consumer can be reduced and more consumers can use the existing transport capacity. To force this change, the reserved transport capacity for each consumer is significantly charged, as outlined in Section 2.3. By implementing this incentive, grid operators aim to increase the utilisation of the available transport capacity and thereby reduce the need for extensive investments for the acquisition of new resources.

The trend of electrification also reached CT operators, resulting in the electrification of CT equipment. Consequently, the total power demand has risen, accompanied by an increased volatility. To accommodate these changes, the gird operator must reserve additional transport capacity for the specific CT. As a consequence, the CTs will experience an increase in their contractual power demand costs. The primary contributors to the peak power demand of a CT are typically STS cranes and reefers [10].

It is important to note that this peak power demand occurs infrequently throughout the year. Consequently, a lot of transport capacity reserved and charged by the gird operator for the CT is not utilised. By implementing peak shaving strategies, the peak power demand can be reduced and thereby the reserved transport capacity. This reduction leads to a direct decrease in the contractual power demand related costs, preferred by the CT operator, and indirectly to a more intensive use of the existing infrastructure, preferred by the grid operator. Nevertheless, it is crucial to minimise the impact of these peak shaving strategies on the productivity of a CT to actual derive economic benefits from their implementation.

## 1.2. Research Objective

Based on the problem statement presented in Section 1.1, CT operators are confronted with the challenge of managing the electrical power demand from electrified equipment to minimise the contractual power demand related costs. Achieving proper power demand management through peak shaving strategies is imperative to minimise contractual power demand related expenses. However, implementing peak shaving strategies may lead to an increase in the handling time, as certain processes must be rescheduled to avoid undesirable peaks in power demand.

The aim of this study is to investigate and identify operational policies that are able to maintain the productivity of a cluster of STS cranes while a peak power limitation is applied for power managing purposes. Geerlings et al. [10] originally proposed the implementation of a peak power limitation as a peak shaving strategy for an entire CT terminal. Building upon the study conducted by Geerlings et al. [10], this research serves as an extension by specifically investigating methods to maintain productivity for a cluster of six STS cranes under increasingly restrictive peak power limitations. It is important to note that Geerlings et al. [10] implemented a peak power limitation on an entire CT comprising of six STS cranes. In contrast, this study focuses on applying a peak power limitation solely on the power demand of a cluster of six STS cranes. This distinction is important to highlight as it distinguishes the scope and scale of the peak power limitation strategy employed in this research compared to the approach taken by Geerlings et al. [10]. The research objective can be summarised as follows:

> "*Developing operational policies that effectively maintain productivity for a cluster of STS cranes under increasingly restrictive peak power limitations*"

### Scientific Relevance

In recent years, numerous studies have been undertaken to explore various peak shaving strategies for STS cranes, as discussed in Section 2.6. However, none of these studies are validated using a simulation model that accurately represents a cluster of STS cranes and the associated yard operations in great detail. Thus, the first scientific contribution of this study lies in the meticulous evaluation of a peak shaving strategy for STS cranes through a highly detailed simulation model.

Furthermore, none of the existing studies have explicitly focused on maintaining productivity while implementing a peak sheaving strategy. Therefore, the secondary scientific contribution of this study is to provide insight into the extent to which productivity of a cluster of six STS cranes can be maintained when applying a peak power limitation.

### Business Relevance

The transition from fossil fuel-powered equipment to electrified equipment is the result of the common goal of reducing GHG emissions. A disadvantage of this transition is the additional reserved transport capacity required to be able to consume the peak power demand, leading to an increase in the contractual power demand related costs. The peak power demand arises when electrified equipment is operating simultaneously, which only occurs occasionally. Reducing the peak power demand saves CTs thousands of euros per month. However, the application of a peak power limitation leads to a decrease in the productivity causing increased handling times, which will cost the CT money. A right balance between reducing the peak power and maintaining productivity can lead to economic advantages. Therefore, operational policies that are able to maintain productivity for a cluster of STS cranes under increasingly restrictive peak power limitations, are of interest to keep electrically powered CT equipment economically attractive.

### Environmental and Societal Relevance

The business relevance of maintaining economically attractiveness of electrically powered equipment directly contributes to the broader environmental and societal goals of reducing local GHG emissions. The electrical peak power consumption is responsible for the set contractual power demand and therefore has a significant attribution to the total electricity costs. If effective solutions to manage this challenge are not implemented, the economic viability of electrification may diminish, resulting in a slowdown in the adoption of electrically powered equipment and hindered progress in reducing local GHG emissions.

This study makes a valuable contribution to the environment and society by evaluating and proposing operational policies as a solution to address the peak power challenge without negatively affecting the productivity. This study aims to encourage and drive further electrification efforts in CTs. By supporting CTs to electrify their equipment, local GHG emissions can be significantly reduced, leading to improved air quality, a positive impact on the environment, and the well-being of surrounding communities.

## 1.3. Research Questions

Based upon the stated research objective outlined in Section 1.2, an academic investigation is formulated. This research seeks to address the main research question by decomposing it into several sub-questions.

### Main Research Question

> "*What is the operational and economic impact of the developed operational policies, aimed at maintaining productivity for a cluster of six STS cranes under increasingly restrictive peak power limitations?*"

### Sub-questions

The following sub-questions provide the foundation for the methodology developed to conduct the research.

1. What are the average characteristics of a Super Post Panamax STS crane? (Chapter 2)
2. What is the power demand of a single STS crane and of a cluster of six STS cranes? (Chapter 2)
3. Which peak savings strategies for STS cranes are published in the literature? (Chapter 2)
4. How does a change in the kinematic characteristics, impact the measured peak power of a single STS crane and its operational time? (Chapter 2)
5. How can the operations of a CT, including the power demand of a STS crane, be accurately represented by a model? (Chapter 3)
6. Which new operational policies can be developed to maintain productivity for a cluster of six STS cranes under increasingly restrictive peak power limitations? (Chapter 4)
7. How can the developed policies be effectively implemented in the simulation model? (Chapter 4)
8. What is the operational and economic impact of the developed policies? (Chapter 5)
9. Which policies can be recommended to maintain productivity for a cluster of STS cranes under increasingly restrictive peak power limitations? (Chapter 7)

## 1.4. Research Scope

The primary objective of this study is to develop and evaluate operational policies that can effectively maintain the productivity of a cluster of six STS cranes, while operating under a peak power limitation. By maintaining productivity, economic advantages can be derived while applying a peak power limitation to reduce the peak power. However, it is important to note that the scope of this study is limited in several aspects.

Firstly, the investigation of the developed policies is focused exclusively on a cluster of six STS cranes. Although it would be interesting to conduct a more extensive analysis that encompasses different cluster sizes, such an investigation was not feasible within the available time. Therefore, this study is limited to the specific configuration of six STS cranes in a cluster.

The ability of STS cranes to regenerate energy during lowering and braking activities is not considered in this study. Including regenerative capabilities would introduce significant variability in the productivity outputs among the replications per experiment, since the benefits taken from the regenerative capabilities are uncontrolled and could strongly differ between the replications. This necessitates additional replications, which would be computationally intensive and impractical within the constraints of this study. Furthermore, including regenerative capabilities would complicate the process of drawing valid conclusions regarding the specific cause-effect relationship between the implemented policies and the productivity outcomes. This is due to the fact that the ability to regenerate power itself and to use it directly in the specific cluster of STS cranes, influences the productivity achieved under a given peak power limitation. Moreover, in order to fully exploit the regenerative energy capabilities, it would be necessary to synchronise the movements of the STS cranes. For instance, a hoisting movement could by synchronised with a lowering movement. Additionally, the integration of an energy storage system (ESS) could further enhance the utilisation of regenerative energy. However, the sizing and characteristics of such a system would require careful consideration to ensure economic feasibility, as studied by Kermani et al. [19, 20]. As a result, this study does not consider energy gains from regenerative movements.

Furthermore, it should be noted that the effect of air resistance on the required power has not been considered in this study. Air resistance could be considered for trolley movements, but the relatively low operational speed of a STS crane results in a negligible impact of the air resistance on the required power. Additionally, air resistance is not constant and depends on the varying wind speed, which complicates the prediction of its influence on the system.

Moreover, all containers handled in the experiments are 40-ft containers, which is equivalent to two twenty-foot equivalent units (TEUs). Additionally, the STS cranes are limited to executing only single movements, meaning that each movement involves the handling of one box, equivalent to two TEU. This restriction was implemented to minimise variations in productivity (measured in handled boxes per hour) across multiple replications of an experiment.

Lastly, this study does not delve into the detailed implementation of the physical systems or computational requirements necessary to execute the developed policies in a real CT. However, it should be noted that in order to implement these policies, certain measuring devices need to be installed, to accurately monitor the current position of the equipment or to monitor the power consumption. Additionally, sufficient computational power must be available to enable real-time decision-making in order to apply the policies effectively and efficiently.

## 1.5. Study Outline

The subsequent chapters of this study are organised as follows. Chapter 2 provides background knowledge related to the problem statement and presents an overview of the peak shaving strategies for STS cranes presented in the literature (Sub-question 1, 2, 3, and 4). In Chapter 3, the simulation model used to assess the developed policies for maintaining productivity under increasingly restrictive peak power limitations is described, validated, and verified. The description includes the applied simulation modelling approach, model parameters, and a detailed description of the simulation model relevant to the research objective (Sub-question 5). Chapter 4 entails a detailed portrayal of the formulated policies (Sub-questions 6 and 7). Furthermore, Chapter 5 presents the outcomes obtained concerning the operational and economic impact resulting from the implementation of the developed policies (Sub-question 8). Chapter 6 discusses key findings, including a comparison with the study conducted by Geerlings et al. [10], limitations encountered during the research process, and recommendations for future research. Finally, Chapter 7 concludes this study by furnishing a comprehensive answer to the main research question and highlighting the contributions of this study to both the literature and the CT industry (Sub-question 9).

Photo: pxfuel

# 2. Ship-to-shore Crane

To address the primary research question, as outlined in Section 1.3, several sub-questions have been formulated. Some of those sub-questions serve the purpose of gaining insight into the present operational status of STS cranes or to examine the existing literature concerning peak sheaving strategies. Those insights plus additional information backing the problem statement are presented in this chapter.

The organisation of this chapter is as follows. At first a brief introduction into the historical evolution of STS cranes is presented in Section 2.1. In Section 2.2 the current state of the art of STS cranes is described. The pricing of electricity is outlined in Section 2.3. Sections 2.4 and 2.5 provide insight into the power demand of a single STS crane and a cluster of STS cranes, respectively. Peak shaving strategies published in the literature are listed in Section 2.6. Based on this literature review several research gaps are identified and discussed in Section 2.7.

## 2.1. Historical Evolution of Ship-to-Shore Cranes

Over the years, the STS cranes' operating principles and design have evolved. Subsection 2.1.1 provides an in-depth analysis of the developments and emergence of the first STS crane. The content of this section is based on the research conducted by van Ham et al. [12], which serves as a fundamental reference for tracing the evolution and origin of the STS crane. Insights into the continued development of STS cranes, specifically regarding their operations and power source, are presented in Subsection 2.1.2.

### 2.1.1. The First Ship-to-Shore Crane

The introduction of steam turbines and diesel engines created a revolution in the shipping industry, enabling ships to travel faster than ever before. This breakthrough led to greater access to overseas territories and boosted global trade. Prior to the onset of World War II, cargo was typically loaded in bags, bales, crates, or casks on general cargo ships. On the quayside, a variety of cranes were employed to handle the diverse cargo.

In 1956, Malcolm McLean established Sea-Land, which was the world's first container shipping company. He embraced the idea of transporting goods in containers. On April 26, 1956, the Ideal X sailed with fifty-eight 33-ft containers from Port Newark, New Jersey to Houston, Texas. This trip marked the start of the containerisation. Malcom McLean gave Brown's Manufacturing Facility the order to further develop the containers. In the beginning, standard whirely cranes were used to handle these containers, as they were the only available cranes in the ports of Newark and Houston. Subsequently, in order to improve the handling rate, Bob Gottlieb and Keith Tantlinger developed the first crane with an automated spreader, as per Malcom McLean's request.

In 1957, Malcolm McLean introduced the C2-class vessels, which had a carrying capacity of 226 35-ft containers. These ships were equipped with shipboard cranes that included a trolley and an automatic spreader, enabling them to call at any port. At the same time, William Matson adopted a different approach by developing dockside cranes for his own similar named shipping company. The first dockside crane was developed and installed at Matson's Encinal Terminal in 1959 in collaboration with manufacturer Paceco, as shown in Figure 2.1. This crane design became the basis for the STS cranes that are commonly used today. Other shipping companies, including Sea-Land, followed this approach. Sea-Land developed their own dockside cranes known as the 'modified A-frame' crane, as depicted in Figure 2.2. The increasing size of container vessels over time necessitated the use of larger STS cranes.

**Figure 2.1:** First dockside crane at Matson's Encinal Terminal in 1959 [12]

**Figure 2.2:** Modified A-frame dockside crane from Sea-Land [12]

### 2.1.2. Further Development of Ship-to-Shore Cranes

As the shipping industry became a competitive market, the need to reduce the handling costs per container was essential to survive. From the first dockside crane at the Matson's Encinal Terminal in 1959, one realised that the STS cranes were the bottleneck restricting the efficiency of the entire CT [17]. Improving the handling rate of STS cranes was marked as the key to reduce container handling costs. Crane manufacturers were ordered to come up with faster STS cranes. To illustrate, the nowadays applied hoisting speed at full load and the trolley travel speed tripled compared to the first dockside crane at Matson's Encinal Terminal [12].

Moreover, in order to keep reducing the operational time of the entire CT, a lot of research has been dedicated to this topic. Varying from creating optimal routes and scheduling schemes for vehicles operating between the STS cranes and the stacking area [9] to optimise the quayside and landside operations planning [37].

Reducing the operational time by implying operational policies was one of the main goals for years. However, in recent times, there has been an increasing demand from international and regional institutions for port authorities to reduce their GHG emissions and promote sustainability [30]. Several options can be applied to reduce the GHG emissions in CTs: (1) equipment measures, (2) energy measures, and (3) energy efficiency measures. Equipment measures include the replacement of older equipment with cleaner and more energy-efficient equipment. Energy measures contain the implementation of alternative cleaner fuels (LNG, methanol, or bio-diesel), alternative power systems (electrification or hybridisation), and renewable energies. Energy efficiency measures include technical or operational measures to reduce the energy consumption (energy management planning, energy storage systems, smart grid, micro grid, and smart load management) [3, 36]. Electrification is suggested as a promising solution to limit GHG emissions in CTs [18]. As a result, STS cranes are electrified, leading to an enormous increase in the electricity demand of CTs and undesired peaks in the electrical power demand [34]. However, although most of the STS cranes are currently electrified, studies devoted to promote the energy-aware operations of STS cranes are still scarce [13, 16].

## 2.2. State of the Art

As outlined in Section 2.1, the evolution of STS cranes and their associated operations has undergone significant transformations throughout the years. This section offers contextual information pertaining to the present state of the art of STS cranes.

A CT is a link in the international transport chain. CTs are divided into the waterside, yard, and landside. The waterside is the operating domain of STS cranes, which are responsible for loading and unloading containers onto and from container vessels according to a predetermined unloading plan. The unloading plan aims to efficiently load and discharge containers and to maintain the stability of the vessel. A container vessel is generally loaded or discharged by a cluster of STS cranes. The number of STS cranes per cluster varies depending on the size of the vessel and the availability of STS cranes.

A STS crane has multiple degrees of freedom and is capable of performing various types of movements. To achieve proper positioning for loading or discharging a container vessel, the STS crane can move horizontally over the quay, a motion referred to as the 'gantry' move. The vertical upward displacement of an container is known as 'hoisting' and the vertical downward displacement of a container is known as 'lowering'. The horizontal movement of a container along the boom girder is carried out with a trolley, which is referred to as 'trolley' move.

There are many different types of STS cranes. Their structural design can be distinguished in two classifications: high-profile STS cranes and low-profile STS cranes. High-profile STS cranes are equipped with a tilting girder boom, while low-profile STS cranes are not. High profile STS cranes have a structure above the boom girder, while low profile STS cranes do not. Low-profile STS cranes, despite being smaller, are structurally heavier and more expensive. The structural design of STS cranes differs per manufacturer. However, all STS cranes are designed to be rigid and stable enough to operate safely and efficiently in varying weather conditions.

The main components of an STS crane are a boom girder, trolley, and spreader. The boom girder is a long horizontal structure that extends over the quay to reach the vessel. The trolley is a movable platform that moves along the boom girder perpendicular to the quay. Moreover, it supports the spreader via cables and pulleys. The spreader is a frame provided with four or eight remote turn-able twist-locks on which the container can be attached.

All STS cranes have a trolley and a spreader. However, to increase the efficiency, new configurations have been developed in recent years. Two conventional trolley systems are the single-trolley system and the dual-trolley system [22]. A single-trolley STS crane has one trolley system. A dual-trolley STS crane has two trolley systems, a waterside trolley and a landside trolley, and a platform halfway the boom girder. The landside trolley transfers containers between the platform and the quay, and the waterside trolley transfers containers between the vessel and the platform. This platform accommodates capacity for multiple containers [22].

The spreader could occur in different configurations [8]. Either a single-hoist spreader or a double-hoist spreader, and either a single-spreader or a tandem-spreader. A single-hoist spreader has one hoist that is used to lift and move the container, whereas a double-hoist spreader has two hoists. A single-spreader system can pick up 2 TEU, either one 40-ft container or two 20-ft containers, as illustrated in Figure 2.3. Lifting two 20-ft containers with a single-spreader is known as ‘twin lifting’. A tandem-spreader can pick up 4 TEU, either two 40-ft containers or four 20-ft containers, as illustrated in Figure 2.3. The single-spreader in combination with a single-hoist is the most conventional combination [5].

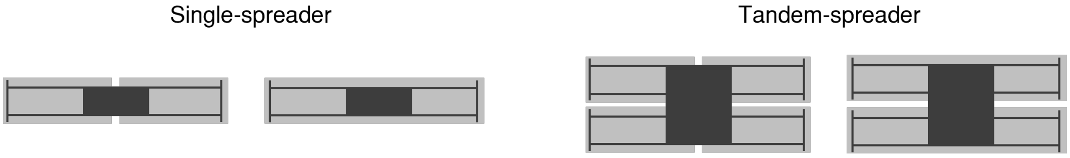



**Figure 2.3:** Possible configurations of a single-spreader and tandem-spreader

Despite multiple different STS crane configurations, their operations are similar. The exported containers are transferred to the STS crane by vehicles (for example by automated guided vehicles or straddle carriers). The spreader picks up the container from the vehicle and transfers it to the vessel. The trolley and hoisting movements often take place at once. Once the container is placed on the vessel the spreader can either pick up an import container from the vessel or move back to the quay without a container. This first option is known as ‘double cycling’. Goodchild et al. found that this load and discharge strategy could reduce the operational time by 10% [11].

Recently, CT equipment, including the STS cranes, are being electrified to reduce the local GHG emissions, leading to an overall increase in the electrical power demand and undesired peak in the power demand of CTs [34]. Moreover, more and more studies are performed which contribute to the energy efficiency within CTs, however this number is still small compared to the studies devoted to promote the handling efficiency [13]. Iris et al. [16] and He et al. [13] presented studies that put an emphasis on the energy-aware planning within CTs.

## 2.3. Pricing of Electricity

The enormous electrical energy demand from CTs places them into the classification of ‘large electricity consumer’. The electricity costs related to this classification can be divided into fixed and variable costs and are outlined in this section. The mentioned prices are based on the charging fees of the Dutch grid operator Stedin in 2023 [31].

### Fixed Costs

The fixed cost consists of the initial investment costs for connecting the CT to the electricity network and a yearly payment for the connection. These fixed costs are based on the applied transport category. Most CTs fit into the ‘Trafo HS+TS/MS’ transport category [14].

### Variable Costs

The variable costs can be distinguished into three parts:

*Actual energy consumption.* Payment for the actual energy demand in euros per kWh.

*Contractual power demand.* Based on the highest expected power demand required by the consumer at any moment in the year a contractual power demand is set. This expectation is, if possible, based on historical data. The demand is charged for 3.0473 euro per kW per month. If there is a significant difference between the actual power demand and the contractual power demand, the grid operator will re-evaluate the contractual power demand. To illustrate, a consumer had a maximum power demand of 10,000 kW in the previous year. No changes are expected for the highest required power demand at any moment in time for the upcoming year. Therefore, the contractual power demand is set to 10,000 kW for the upcoming year, as a result the consumer has to pay 365,676 euro as contractual power demand costs for that specific year.

*Maximum power demand.* For each 15-minute time interval, unless otherwise agreed with the grid operator, the average power is logged. The maximum observed average power demand over a 15-minute time interval is charged for 4.0649 euro per kW per month, referred to as maximum power demand costs. These costs are charged for the upcoming twelve months. To illustrate, a consumer has a maximum average power demand (measured over a 15-minute time interval) of 5000 kW, as a result the consumer has to pay 20,324 euro monthly, for the next twelve months. However, if after two months a higher maximum average power demand of 6000 kW (measured over a 15-minute time interval) has been measured, the monthly fee becomes 24,389 euro for the next twelve months.

## 2.4. Power Demand of a Single STS Crane

The Super Post Panamax STS cranes are currently used to handle the largest container vessels [32], with capacities up to 11.000 TEU. Therefore, its characteristics are used to plot an ‘average’ power profile. The trolley, hoisting, and lowering characteristics of an average Super Post Panamax STS crane are respectively presented in the Tables B.1 and B.2. These values were obtained from eight STS crane manufacturers: Kalmar, Konecranes, ZPMC, Doosan, IMCC, Liebherr, Mitsubishi, and Generic [7]. The formulas required to calculate the power at each time instance are presented in Appendix B.

Figure 2.4 provides an overview of the power profile during an export cycle for a Super Post Panamax STS crane, as depicted in Figure B.1. The power profile demonstrates the variation in power consumption throughout the different stages of the cycle. During the initial phase of the cycle, a loaded container weighing 40 tonnes is hoisted. During the acceleration phase of this movement a peak power value is observed of 1954 kW. Thereafter, the trolley moves from the landside to the waterside. During the deceleration phase of this movement, there is potential for power regeneration, by converting kinematic energy into electrical energy. Afterwards, the container is lowered onto the container vessel. Similarly, during this lowering phase, there is potential for power regeneration, by converting potential energy into electrical energy. Once the container is loaded onto the vessel, the spreader is hoisted without a load. This results in lower power values for the hoisting, trolley, and lowering movements compared to when a container is being handled.

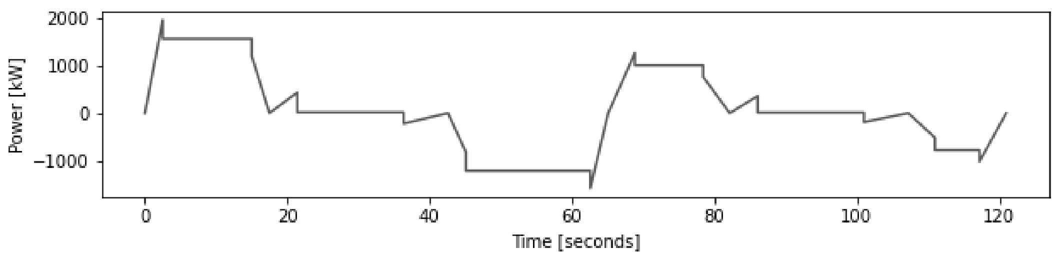



**Figure 2.4:** Power demand profile of an average Super Post Panamax STS crane (export cycle)

## 2.5. Power Demand of a Cluster of Six STS Cranes

To analyse the power demand pattern of a cluster of six STS cranes, an experiment is conducted where all six STS cranes operate simultaneously for a duration of three hours at balanced CT settings, as outlined in Subsection 3.1.2. Figure 2.5 presents the observed power profile during the conducted experiment. The power profile reveals the dynamic nature of the power demand, showcasing the variations and changes over time.

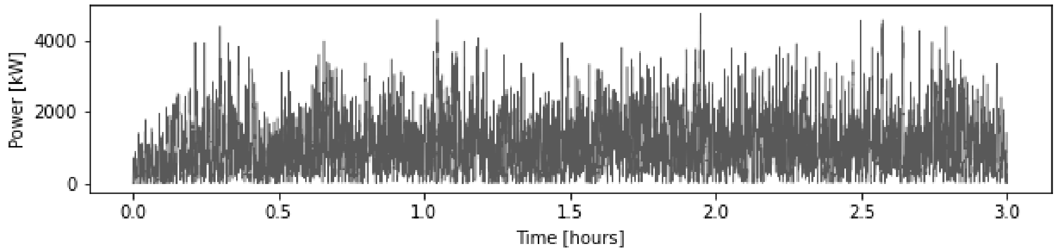



**Figure 2.5:** Power demand profile for a cluster of six Super Post Panamax STS cranes at 'balanced' CT settings

In addition to analysing the power profile of a cluster six STS cranes, a further investigation was undertaken to examine the frequency distribution of specific power ranges. This analysis aimed to assess the occurrence and distribution of power levels within predefined ranges. Figure 2.6 provides an overview of the frequency distribution of the observed power demand during the conducted experiment. The power values included are the average power values over one second. The power values equal to zero are not included in the analysis. Based on the frequency distribution, it is evident that the elimination of the highest observed powers, due to their low frequency of occurrence, are unlikely to have a significant impact on the STS cranes' productivity. On the other hand, decreasing the power limitation further, will have probably a noticeable effect on the productivity of the STS cranes.

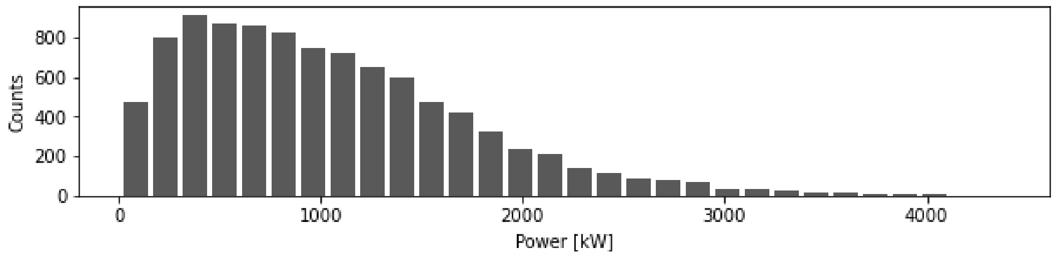



**Figure 2.6:** Power demand of a cluster of six Super post Panamax STS cranes categorised

## 2.6. Peak Shaving Strategies in the Literature

High peaks in electricity demand occur when electrically driven terminal equipment is operating simultaneously to handle container vessels as quickly as possible [10, 19, 20]. Peak shaving strategies applied by the CT's operator are required to suppress the contractual power related costs. Various peak shaving strategies are presented in the literature and can be categorised in three categories: (1) Power Sharing: store energy in a non-peak period and use it in a peak period, (2) Load Shifting: shift loads from a peak period to a non-peak period, (3) Load Shedding: turn off loads during a peak period [16].

An overview of the studied peak shaving strategies for STS cranes in the literature is presented in Table 2.1. The applied measures of the peak shaving strategies can be classified into three groups:

(1) operational constraint (OC), (2) regenerative energy (RE), and (3) ESS. The measure to use regenerated energy is either combined with an ESS (an ultracapacitor (UC) or a flywheel (FW)) or with an OC. In combination with an ESS, the ESS is charged during lowering and braking activities. In combination with an OC, lowering and hoisting movements are aligned such that the regenerate energy by one crane can directly function as power source for another crane.

The performance of the peak shaving methods in the literature are most often expressed by the load factor or by the percentage change of the initial peak power. The load factor is defined as the average power divided by the peak power. The impact on the overall CT productivity, expressed as the amount of boxes handled per time unit, is most often not included.

**Table 2.1:** Overview of peak shaving strategies studied in literature

| ID | Method | Approach | RE | ESS (power kW) | OC | Result Peak power reduction (grid) | Reference |
|---|---|---|---|---|---|---|---|
| 1 | System design | UC in crane drive, charged by RE and grid (constant) | Yes | UC (1350) | No | -90% | [26] |
| 2 | System design | UC in crane drive, charged by RE | Yes | UC (905) | No | -60% | [27] |
| 3 | Optimisation | Fixed delay between DCs | No | No | Yes | -43% | [28] |
| 4 | | + ESS charged by RE | Yes | UC (1908), FW (3375) | Yes | -74% | |
| 5 | Particle Swarm Optimisation | Fixed delay between DCs (11s) | Yes | No | Yes | -82% | [19] |
| 6 | | Variable delay between DCs | Yes | No | Yes | -82% | |
| 7 | Discrete-event Simulation | Limiting simultaneously hoisting | No | No | Yes | -38% | [10] |
| 8 | | Limiting max. energy demand | No | No | Yes | -48% | |
| 9 | Agent-based Simulation | Limiting simultaneously hoisting. With double cycling mode. | No | No | Yes | -37% | [33] |
| 10 | | Limiting max. energy demand. With double cycling mode. | No | No | Yes | -58% | |
| 11 | Hierarchical control strategy | UC in crane drive charged by RE | Yes | UC (2048) | No | -49% | [21] |
| 12 | Particle Swarm Optimisation | DC coordination | Yes | No | Yes | -44% | |
| 13 | | + UC in crane drive charged by RE | Yes | UC (unknown) | Yes | -62% | |

duty cycle (DC)

## 2.7. Research Gaps

As mentioned in Subsection 2.6, the impact of the peak shaving strategies published in the literature on the productivity of STS cranes has often not been comprehensively studied. Even when productivity is considered, it is typically assessed through simulation studies that lack a profound representation of the complexity involved in a CT. For instance, Geerlings et al. [10] conducted a study to evaluate the effects of their peak shaving strategy using a discrete event simulation model, wherein the yard operations and STS crane activities were simplified. This highlights the first research gap, which is the lack of detailed evaluation of peak shaving strategies using advanced simulation software that can accurately model the intricacies of CT operations.

Another research gap is the limited consideration of costs in the evaluation of peak shaving strategies. Most literature focuses solely on reducing the peak power, without analysing the associated costs. It is essential to consider the economic implications of these strategies to understand their feasibility and potential benefits.

Furthermore, none of the literature sources presented in Table 2.1 have specifically addressed the objective of maintaining productivity for a cluster of STS cranes while applying a peak shaving strategy. This highlights the need for strategic operational policies that can effectively balance the reduction in peak power with the preservation of productivity.

Moreover, none of the literature sources presented in Table 2.1 have focused on reducing the peak power of a STS crane by modifying its kinematic behaviour. While, as presented in Appendix C, kinematic adaptations can significantly impact the peak power. However, these adaptations also have a negative effect on the overall productivity of the STS crane. To illustrate, hoisting a 40-ton container at an acceleration rate of 0.8 $m/s^2$ towards a velocity of 1.5 $m/s$ results into a peak power of 1954 kW. However, hoisting a 40-ton container at an acceleration rate of 0.3 $m/s^2$ towards a velocity of 1.3 $m/s$ results into a 23% reduction of the measured peak power and into a 3.6% increase in the total export cycle time.

Geerlings et al. [10] conducted a study aimed at reducing the electrical peak power demand of a CT by implementing a peak power limitation. This rule of operation implies that a STS crane requests the estimated power consumption before initiating a movement. Subsequently, the simulation model verifies if the requested power is available. If not, the crane is temporarily halted until sufficient power becomes available, following a ‘first come first serve’ approach as outlined in Subsection 3.2. However, despite this approach being described in the literature, multiple alternative approaches for implementing a peak power limitation have not been explored yet.

Overall, these research gaps highlight the need for more comprehensive studies that consider the detailed evaluation of peak shaving strategies using advanced simulation software, incorporate cost analysis, and focus on maintaining productivity while mitigating the highest observed peak power values. Consequently, the objective of this study is to extend upon the work conducted by Geerlings et al. [10] by exploring the implementation of peak power limitations on specifically STS cranes using various approaches and by making use of adapted kinematic profiles. This research aims to gain insight into the extent to which different implementations of a peak power limitation can maintain productivity under increasingly restrictive peak power limitations for a cluster of six STS cranes.


# 3. Methodology

The objective of this study is to develop and evaluate new operational policies to keep up the productivity of a cluster of six STS cranes while a peak power limitation is applied. It is impossible, financially and operationally, to test these policies in real-life. Moreover, the operational complexity of the CTs makes it impossible to recreate a CT in an experimental miniature version on a short term basis. Therefore, these policies must be modelled. Models can be categorised into analytical and simulation models. In an analytical model the result depends on the input parameters and a simulation model contains rules that impact the system that is modelled [6].

Simulation is recommended as an effective methodology to test policies within an environment that has many parameters with a high level of uncertainty or when the structure of the problem is too unpredictable or challenging to accurately translate it into an analytical formulation [6, 23]. Since this is the case for a CT, the operational policies suggested within this study will be evaluated through simulation.

In Section 3.1 the developed simulation model is described. The parts of the simulation model directly related to the research objective are described in Section 3.2. The experiments done to verify the model are presented in Section 3.3. In Section 3.4 the simulation model is validated by comparing the estimated power with the actual power, this section also includes the results of the base scenario. Lastly, a sensitivity analysis is conducted on the effect of the applied simulation time on the measured peak power in Section 3.5.

## 3.1. Development of the Simulation Model

This section contains a description of the developed simulation model. A small overview of different simulation approaches is outlined in Subsection 3.1.1, followed by the argumentation for the chosen simulation approach. The most relevant model parameters for this study are presented in Subsection 3.1.2.

### 3.1.1. Simulation Modelling Approach

In the literature, multiple approaches are used to model a CT. These approaches can be categorised as programming-based or mathematics-based. The programming-based approaches can be further categorised as objected-oriented programming or agent-oriented programming [38].

The three major paradigms in simulation modelling are: System Dynamics, Discrete Event, and

Agent Based modelling [4, 6, 24]. These modelling approaches can be classified based on their abstraction level, as illustrated in Figure 3.1. A general overview of these simulation modelling approaches is presented below.

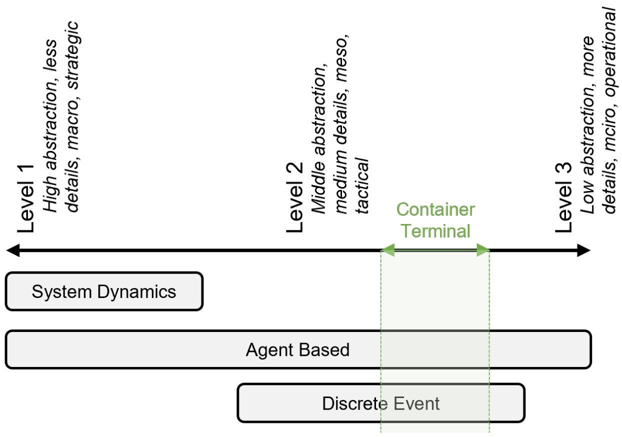



**Figure 3.1:** Three major paradigms in simulation modelling [6]

### System Dynamics Simulation Model

System dynamic modelling focuses on capturing the interrelationships and dependencies among various components within a system rather than individual details. The dependencies among the various components are represented with feedback loops. A system dynamics simulation model is commonly employed to simulate abstract systems over an extended duration, enabling the assessment of strategic actions for real-life decision-making [4].

### Agent Based Simulation Model

The behaviour in agent based models is defined at individual level. All individuals (agents) have their own set of rules, behaviours, and decision-making processes. These agents are autonomous, responsive, and proactive. They are able to communicate with each other and the environment. The global behaviour emerges as a result of all the individuals. Agent based models are therefore known as 'bottom-up modelling' [6].

### Discrete Event Simulation Model

The objects in discrete event models can be described as entities. Entities are passive objects that could represent tasks, equipment, documents, etc. They travel through the system where they stay in queues, are processed, combined, etc. In discrete-event simulations the system's state is updated only at discrete points in time, known as the 'events' [6].

### Choice of Modelling Approach

In the philosophy of the study of Borshchev et al. [6], a CT fits between level 2 and level 3 based on its abstractness, as illustrated in Figure 3.1. Indicating that a discrete event and an agent based simulation model are both suitable for modelling a CT. Moreover, via a search conducted in SCOPUS using the search terms "Container Terminal" OR "port" AND the specific modelling approach, it was found that there is a significant number of publications related to both discrete event simulation and agent based simulation in the context of CTs. However, the majority of the publications (379 documents) were focused on discrete event simulation, while a smaller number of publications (70 documents) were related to agent based simulation. Therefore, discrete event simulation using the Tecnomatix Plant simulation modelling tool, is used in this study to model and evaluate the policies.

### 3.1.2. Model Parameters

This subsection provides the most relevant model parameters for this study. These parameters include the ones that directly impact the operational and economic impact of the developed policies. The policies are evaluated in the same CT layout but at different CT settings. These settings differ in the amount of applied operational equipment serving the STS cranes. The terminal layout, applied equipment, and an overview of the different CT settings is provided first. Thereafter, the container loading/discharge plan is outlined even as the container weight distribution.

#### Terminal Layout and Equipment

Figure 3.2 provides a cross-section of the simulated CT layout. The CT consists of a cluster of six dual-trolley STS cranes responsible for loading and unloading container vessels. The waterside trolley-spreader combination facilitates the transfer of containers between the container vessel and the platform, while the landside trolley-spreader combination facilitates the transfer of containers between the platform and the automated guided lift vehicles (AGLVs). The AGLVs transfer the containers between the STS cranes and the stack. At each time two AGLVs can wait below a STS crane. The AGLVs and the waterside rail mounted gantry (RMG) crane interact with each other via an interchanging point. At this interchanging point, containers are placed on a structure either by the waterside RMG crane or the AGLV, and picked up by the corresponding equipment for further handling. The stacks in the CT are perpendicular arranged to the quay wall and have 34 bays, 10 rows, and 5 tiers. To illustrate, 850 (17x10x5) 40-ft containers can be stacked in one stack. Furthermore, two RMG cranes are operating in one stack, one on the waterside and one on the landside. The RMG cranes are bounded to one stack and cannot pass each other.

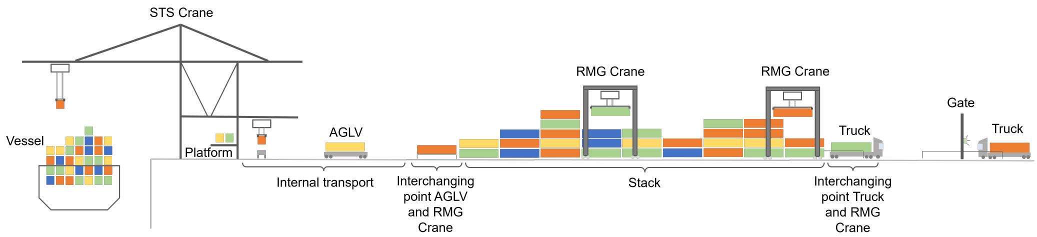



**Figure 3.2:** Cross-section of the simulated CT

To evaluate the relation between the performance of the policy and the terminal operations, two scenarios are developed, each representing a different situation regarding the limiting factor of the STS cranes. The scenarios are outlined in Table 3.1. The main difference between both CT settings is the influence of a denied movement, due to a lack of power, on the productivity. In the first scenario, the CT operations are balanced, meaning that the STS cranes, AGLVs, and RMG cranes operate at levels that closely resemble realistic CT settings and neither of them can be appointed as the bottleneck regarding the overall CT productivity. In this setting it is likely that a STS crane has to wait for an AGLV to arrive. Meaning that additional waiting times caused by a lack of power might not have a direct adversely impact on the productivity. In the second scenario, the impact of the AGLVs and RMG cranes on the STS cranes' productivity is limited. In this setting it is likely that the STS crane does not have to wait for an AGLV to arrive. Meaning that additional waiting times caused by a lack of power directly influence the productivity negatively.

Moreover, the second CT setting makes it possible to state independent conclusions about the influence of the policy on the productivity, since it is not impacted by the AGLVs or RMG cranes. To illustrate, when there is no peak power limitation applied, the STS cranes have a relatively high productivity, leading to a higher chance that a STS crane has to wait for an AGLV to arrive. However, when a peak power limitation is applied, the STS cranes will have a lower productivity, resulting in a lower chance that a STS crane has to wait for an AGLV to arrive. Therefore, the number of operating AGLVs has a relatively higher restricting influence on the productivity when no peak power limitation is applied. By means of an experiment, described in more detail in Appendix D, it is found that 35 AGLVs operating at an unrealistic high velocity and a stacking yard consisting of 31 stacks are required to limit the impact of the AGLVs and RMG cranes on the STS cranes' productivity

**Table 3.1:** Terminal layout and equipment scenarios

| Scenario | STS cranes | Productivity (ls)* | AGLVs | Productivity | RMG stacks | Productivity (ws)* |
|---|---|---|---|---|---|---|
| Balanced | 6 | 58.8% | 25 | 45.7% | 12 | 78.4% |
| STS crane limiting | 6 | 65.5% | 35** | 52.3% | 31 | 31.4% |

*Percentile of total operating time in which specific equipment is productive for the landside (ls) or waterside (ws)
**Operating at an unrealistic high velocity

#### Container Loading/Discharge Plan

To minimise the impact of the container loading/discharge plan on the peak power and handling rate, containers are loaded on and discharged from the container vessel evenly. 22.5% of the loaded containers are empty, 5% are reefers, and 72.5% are regular containers. 5% of the discharged containers are empty, 5% are reefers, and 90% are regular containers. Moreover, within this study only 40-ft containers are handled via a single-spreader.

#### Container Weight Distribution

The handled containers differ in weight. The applied weight distribution is presented in Table 3.2.

**Table 3.2:** Container weight distribution

| **Weight [ton]** | 0 | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|---|---|---|---|
| **Distribution** | 0 | 0 | 0.13 | 0.34 | 0.55 | 0.75 | 0.95 | 0.99 | 1 |

## 3.2. Description of the Simulation Model

The discrete event simulation model employed in this study is built upon the foundational simulation model developed by Portwise. This simulation model serves as a representation of a fictitious CT in very high detail. In order to address the research question, new modules have been specifically designed and integrated into the existing model. In this section only the modules of the simulation model that are directly related to the research objective are discussed.

### 3.2.1. Implementation of the Peak Power Limitation

A peak power limitation, suggested and studied by Geerlings et al. [10], is applied in this study as the peak shaving strategy. In this strategy the power of an upcoming movement is estimated. Thereafter it is checked whether this power fits within the applied peak power limitation. If the movement fits, the specific equipment gets permission to start immediately, if not, the movement is postponed after which it is checked again if power is available.

The corresponding 'power constraint' is presented in Equation 3.1. Where the estimated power ($EP$) at each time instance $i$ should remain lower than or equal to the applied peak power limitation ($PPL$) minus the reserved power ($RP$) by other equipment at that same time instance $i$. The set $I$ represents the time values of the specific movement in increments of one-tenth of a second ($[t_{now}, t_{now+0.1}, ..., t_{end-0.1}, t_{end}]$).

$$EP_i \leq PPL - RP_i \; \forall \; i \epsilon I \tag{3.1}$$

### 3.2.2. Approach

Geerlings et al. [10] implemented their peak shaving strategy according to the 'first come first serve' approach. However, multiple approaches can be applied as outlined in this subsection. The 'who fits is served' and 'priority based' approaches will be evaluated and compared in this study on their operational and economic impact under increasingly restrictive peak power limitations. The multiple approaches are briefly described below. In Chapter 4, the implementation of the approaches in the developed policies is described in more detail supported by flowcharts.

#### I. Who fits is served

When the estimated power fits within the available power, the movement gets permission to start immediately. If not, the start of the movement is postponed for a certain period of time. After this time period it is again checked whether the estimated power fits within the available power. Within this time period other equipment is allowed to make a request and to start a movement. This cycle repeats itself until the movement gets permission to start.

#### II. First come first serve

When the estimated power fits within the available power, the movement gets permission to start immediately. If not, the start of the movement is postponed for a certain period of time. After this time period it is again check whether the estimated power fits within the available power. Within this time period other equipment is not allowed to make a request to start a movement. This cycle repeats itself until the movement gets permission to start.

#### III. Priority based

At first, the requested movement gets a priority number based on the status of the AGLV and platform. For example, if the AGLV is already at the interchanging point, then the trolley movement towards the interchanging point will get a high priority (low value). If either this priority number is lower or equal to the listed priority numbers of waiting movements and the estimated power fits within the available power, the movement gets permission to start immediately. If the priority number is higher than the listed priority numbers of other waiting movements or the estimated power fits not within the available power, than the priority number of the specific movement is listed. After a certain time period the request is re-evaluated according to the same cycle. This cycle repeats itself until the movement gets approval to start.

### 3.2.3. Movements Ship-to-Shore Crane

A container vessel is loaded and discharged by six STS cranes. As noted in Section 3.1.2 the STS cranes have two trolleys, two spreaders, and a platform with a capacity of two containers.

The trolleys are able to perform two types of movements: (1) trolley to waterside and (2) trolley to landside. Both trolley movements consume power. The spreader has four types of movements: (1) hoist to safety distance, (2) hoist from safety distance, (3) lower to safety distance, and (4) lower from safety distance. The 'hoisting' movements consume power. The 'lowering' movements regenerate energy. Important to note is that the regenerated energy is not utilised within this research, as outline in Section 1.4.

### 3.2.4. Estimation of the Power Demand

The estimation of the power for both the trolley and spreader movements is a critical aspect in ensuring that the actual power is kept below the peak power limitation. This subsection provides a concise overview of the power estimation process for these movements.

The power profiles of the trolley and spreader (hoisting only) are depicted in Figure 3.3. These profiles are assumed to follow a linear pattern and can be divided into multiple line segments, each representing a specific phase of the movement. Line segments $l_1$ and $l_3$ correspond to the acceleration phase, while $l_2$ and $l_4$ represent the movement at a constant velocity. Lastly, segment $l_5$ represents the deceleration phase. The transition between these segments is indicated by the time values $t_0$, $t_1$, $t_2$, $t_3$, $t_4$, and $t_5$.

For the spreader movement, an additional acceleration state is present. This is due to the imposed speed limitation of 0.54 $m/s$ during the initial part of the hoisting movement. Once the safety distance is reached at time instance $t_2$, the velocity is increased to the maximum allowable value.

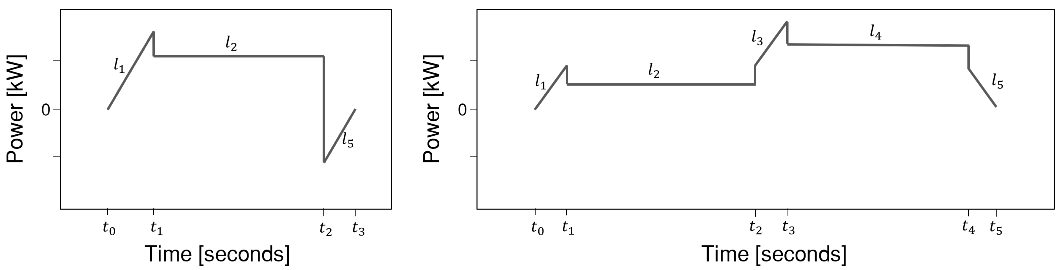



**Figure 3.3:** Power profile of the trolley (left) and spreader (right)

To ensure an accurate estimation of the power demand, the time values are determined first. An important aspect of the accuracy of the estimated power is the time interval at which the estimated power is calculated, at each second, for each tenth of a second, or for each hundredth of a second. Due to computational limitations, both the actual power and estimated power are recorded every tenth of a second for each movement. Additionally, to ensure that the peak power is captured, the values of $t_1$ and $t_3$ are rounded up.

For instance, in the case of a trolley movement, the values of $t_0$, $t_1$, $t_2$, and $t_3$ are determined to be 2.943, 5.8846, 9.4564, and 12.6824, respectively. The boundaries for the line segments $l_1$, $l_2$, and $l_3$ are set to [3.0, 5.9], [6.0, 9.4], and [9.5, 12.6], respectively. Once the boundaries of the line segments are established, the power at each tenth of a second can be calculated for each line segment using the formulas presented in Table 3.3.

The speed fraction ($sf$) is calculated by dividing the velocity at a specific time interval by the maximum allowed velocity for a 40-ton container. Similarly, the weight factor ($wf$) is calculated by dividing the weight of the container by 40 tonnes, which is the maximum container weight. The power

**Table 3.3:** Power formulas per line segment

| Line segment | Formula |
|---|---|
| $l_1$ | $P_{l1}(t) = \frac{(P_{max0t}+((P_{max40t}-P_{max0t})*wf))*sf}{t_1-t_0} * t$ |
| $l_2$ | $P_{l2}(t) = (P_{nom0t} + ((P_{nom40t} - P_{nom0t}) * wf)) * sf * t$ |
| $l_3$ | $P_{l3}(t) = \frac{(P_{max0t}+((P_{max40t}-P_{max0t})*wf))*sf}{t_1-t_0} * t + P_{l1}(t_1)$ |
| $l_4$ | $P_{l4}(t) = (P_{nom0t} + ((P_{nom40t} - P_{nom0t}) * wf)) * sf * t$ |
| $l_{5,trolley}$ | $P_{l5}(t) = \frac{(P_{min0t}+((P_{min40t}-P_{min0t})*wf*-1))*sf}{t_3-t_2} * t$ |
| $l_{5,spreader}$ | $P_{l5}(t) = \frac{(P_{min0t}+((P_{min40t}-P_{min0t})*wf*-1))*sf}{t_5-t_4} * t$ |

values $P_{max}$, $P_{nom}$, and $P_{min}$ represent the maximum power used for a specific container weight (0 or 40 tonnes), for the acceleration, constant velocity, and deceleration state, respectively. These power values are calculated based on the power formulas and the crane characteristics, detailed in Appendix B.

## 3.3. Verification

To test if the basis of the simulation model (presented in Subsection 3.2.1) is working properly, several verification tests were conducted to assess its functionality. The tests aimed to investigate the impact of certain factors on the model's behaviour. The tests and their corresponding hypotheses are outlined below:

1. Test: increase $P_{max}$.
   Hypothesis: a higher $P_{max}$ setting will result in an overall increase in the total energy consumed.
2. Test: modified container weight distribution, favouring heavier containers for loading and unloading operations.
   Hypothesis: handling heavier containers will lead to a higher total energy consumption.

Both tests were performed, and the hypotheses were confirmed. These results indicate that the simulation model is functioning correctly and aligns with the expected behaviour.

## 3.4. Validation

Before executing the experiments for the formulated policies and interpreting the results from these experiments a few more things have to be determined and checked. At first the required number of replications per experiment has to be determined. The methodology applied to determine the amount of replications per experiment and the corresponding results are presented in Section 3.4.1. In Section 3.4.2 the model is validated by comparing the output of the estimating power module with the actual power consumed. Finally, the result of the base scenario at two different CT settings is presented in Section 3.4.3.

### 3.4.1. Required Number of Replications

#### Methodology

To achieve accurate results from the experiments for the formulated policies, a specific number of replications has to be conducted per experiment. The approach employed to ascertain the required number of replications per experiment in this research is grounded on the methodology presented by K. Hoad et al. [15].

Initially, the required level of precision ($d_{required}$) is determined. This precision is quantified as a percentage deviation of the cumulative mean, which is deemed acceptable within a specific confidence interval. To illustrate, if the predetermined precision is 5%, cumulative mean 100, and the set confidence interval 95%, there is a 95% probability that the true average value falls within the interval of [95,105].

The level of precision for a given number of replications ($d_n$) can be expressed using Equation 3.2 [29]. Here, $n$ represents the current number of replications conducted, $t_{n-1,\frac{\alpha}{2}}$ denotes the student t-value for $n-1$ degrees of freedom and a significance level of $1-\alpha$. $S_n$ is the estimated standard deviation, and $\bar{X}n$ refers to the cumulative mean. The values of $Sn$ and $\bar{X}n$ are obtained using the results $Xi$ ($i = 1$ to $n$) obtained from the $n$ replications completed so far.

$$d_n = \frac{100 t_{n-1,\frac{\alpha}{2}} \frac{s_n}{\sqrt{n}}}{\bar{X}_n}, \tag{3.2}$$

The level of precision ($d_n$) is determined for an initial number of replications, $n$. An additional replication is performed if $d_n$ exceeds the required precision ($d_{required}$). Once $d_n$ falls below $d_{required}$, a few more replications (specified by the parameter $limit$) of the model are conducted to verify that $d_n$ remains within the required precision. If this is the case, the required number of replications ($n_{required}$) is equal to $n$. However, if $d_n$ appears to be greater than $d_{required}$ for one of the extra replications, an additional replication is performed. This algorithm for determining the number of replications is outlined in Figure 3.4.

$n = 3$
Set $d_{required}$
Set $limit$

Run $n$ replications of the model

Calculate $d_n$

While $d_n > d_{required}$
    $n = n + 1$
    Run an extra replication of the model
    Calculate $d_n$

If $d_{n+1}, \ldots, d_{n+limit} \leq d_{required}$
    $n_{required} = n$
Else
    Perform one more replication and go back to the while loop

End of method

**Figure 3.4:** Replication algorithm to determine the required number of replications

#### Results

According to a set of tests, the peak power output of six STS cranes is estimated to be around 5000 kW. In order to ensure a satisfactory level of precision and confidence, a 5% precision and a 95%

confidence interval were chosen. This selection yields a range of acceptable values of [4750, 5250] and requires a feasible number of replications given the available resources. Applying the specified replication algorithm to these conditions, the requisite number of replications is determined to be 14. Figure 3.5, depicts the outcomes of this methodology.

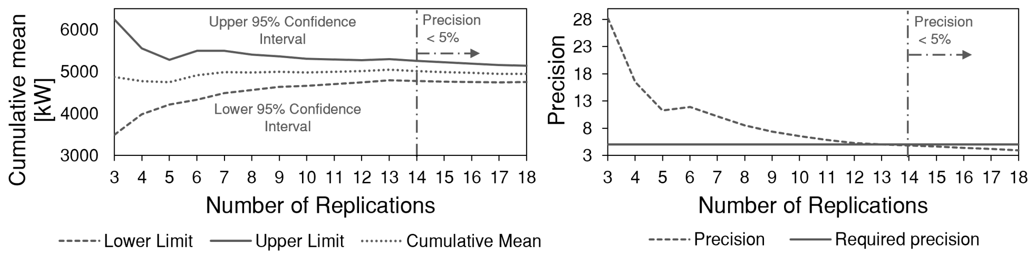



**Figure 3.5:** Graphical output of the replication algorithm

## 3.4.2. Validation of the Simulation Model

A validation is performed on the estimated power module to check whether the estimated power matches the actual power and to check if the measured peak power lies below the applied peak power limitation. For the validation of the estimated power module the actual power and estimated power between the two hundredths of a second and the four hundredths of a second are compared. Within this time period of ten minutes six STS cranes are operating under the restriction of a peak power limitation of 2200 kW.

The estimated power and the actual power are plotted in Figure 3.6. Both lines show the same pattern, indicating that the estimated power module works properly. At all time, the estimated power is slightly higher than the actual power, this is in line with the set up of the model, as explained in Section 3.2.4. Moreover, the applied peak power limitation of 2200 kW has not been exceeded.

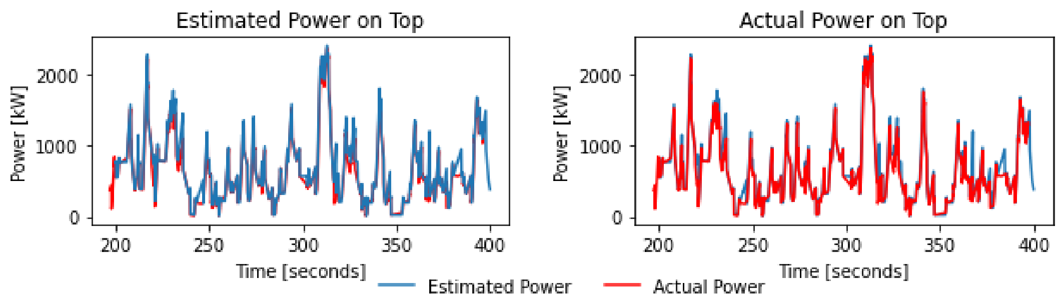



**Figure 3.6:** Estimated power vs. Actual power

## 3.4.3. Results Base Scenario

In order to establish a baseline scenario for this study, an experiment was conducted consisting of 14 replications to capture the peak power under normal operating conditions without any imposed restriction. Each replicate had a run time of 3 hours. A baseline scenario was created for both CT settings. The key figures of this scenario are listed in Table 3.4. The peak power presented in Table 3.4 is the maximum peak power measured in all the replications and the yearly contractual power demand costs are based on the peak power measured.

**Table 3.4:** Performance of the base scenario

| CT Settings | Peak Power [kW] | Contractual Power Demand Costs [euro/year] | Productivity [box/hour] |
|---|---|---|---|
| Balanced | 5,541 | 202,621 | 30.0 |
| STS crane limiting | 5,751 | 210,300 | 32.5 |

## 3.5. Sensitivity Analysis Peak Power

The results of the base scenario, as discussed in Subsection 3.4.3, were obtained using a simulation time of three hours per experiment. In order to assess the impact of the simulation time on the measured peak power at balanced CT settings, a sensitivity analysis was conducted. The peak power values were measured for different simulation times, and the results are summarised in Table 3.5. The number of replications for the experiments with increasing simulating times was reduced due to computational limitations.

**Table 3.5:** Sensitivity analysis peak power at balanced CT settings

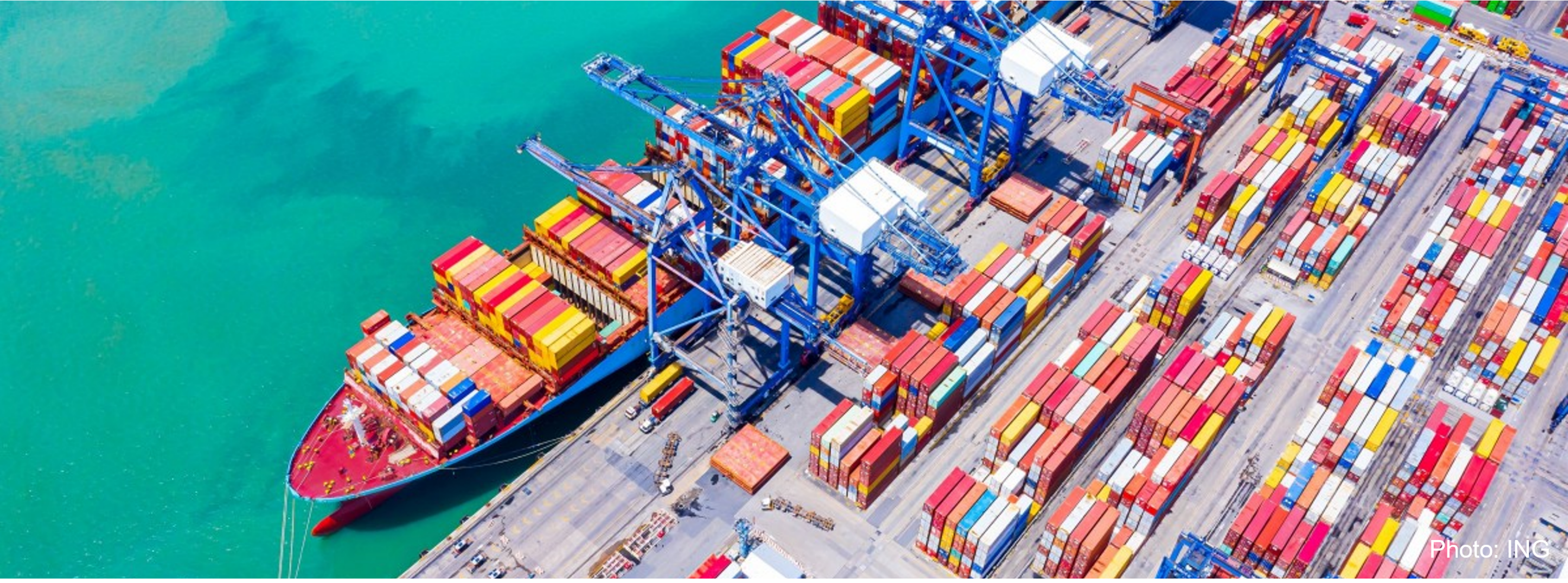
| Simulation time [hour] | Peak power per replication [kW] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Max. |
| 3 | 4779 | 5131 | 4679 | 5541 | 4958 | 4746 | 4536 | 5466 | 4787 | 4979 | 4691 | 5541 |
| 6 | 5784 | 5357 | 5911 | 5060 | 5225 | 4358 | 5266 | | | | | 5911 |
| 9 | 5787 | 5240 | 5313 | 5399 | 4647 | | | | | | | 5787 |
| 12 | 5201 | 5193 | 4722 | 5597 | 5454 | | | | | | | 5597 |
| 15 | 5341 | 5543 | 6168 | 5138 | 5576 | | | | | | | 6168 |

As outlined in Subsection 3.4.1, the initially determined required number of replications for a simulation run of three hours was 14. However, during the analysis in Chapter 5, some outliers in terms of productivity were observed. To make a fair comparison between the experiments, it was aimed to achieve a standard deviation of one for the productivity. To achieve this, outliers in terms of productivity were eliminated. Consequently, the final number of replications for the three-hour simulation run was reduced to 11, instead of the initially determined 14.

Table 3.5 provides insight into the relationship between the simulation time and the measured maximum peak power. The maximum peak power values obtained for each simulation time are listed in the last column. Comparing the results to the three-hour simulation time, it can be observed that the six-hour simulation time resulted in a 6.7% increase in the measured maximum peak power. The nine-hour simulation time showed a 4.4% increase, the twelve-hour simulation time showed a 1.0% increase, and the fifteen-hour simulation time showed a 11.3% increase.

It is important to note that, except for the fifteen-hour simulation time, the maximum measured peak power did not consistently increase with longer simulation times. However, it is worth mentioning that the third replication of the fifteen-hour simulation run is an outlier compared to the other peak powers measured in the fifteen-hour simulation run. Therefore, it should be interpreted with caution, and further replications for all simulation times would be necessary to draw more definitive conclusions.

It can be concluded that the simulation time does not consistently impact the measured maximum peak power, as the values observed fall within a range of approximately 5500 kW to 6200 kW. However, caution should be exercised when interpreting the peak power values obtained from a three-hour simulation run, as they may not represent the absolute maximum peak power that can be reached. Further analysis and experimentation with longer simulation times and more replications may be necessary to fully explore and understand the upper limits of the peak power in this context. This study does not specifically focus on obtaining the exact peak power for a CT with six operating STS cranes, and therefore, the deviation in the peak power can be justified.




# 4. Developed Policies

This chapter provides a detailed description of the developed policies. The methodology and working principle for each policy is described in detail in Section 4.1, 4.2, 4.3, and 4.4 for policy 0, policy 1, policy 2, and policy 3, respectively. A brief overview of the developed policies is presented in Table 4.1. These policies are developed within this study with the objective to maintain productivity under increasingly restrictive peak power limitations. The policies employing a 'priority based' approach utilise the real-time status of interacting equipment, and hence, are solely evaluated under balanced CT settings.

**Table 4.1:** Overview of the developed policies

| | | | | |
|---|---|---|---|---|
| **Scope:** | Cluster of 6 STS cranes | | | |
| **Methodology:** | Discrete event simulation | | | |
| **ID** | **Peak Shaving Strategy** | **Approach** | **Kinematic Profile(s)** | **CT Setting** |
| Policy 0 | Peak power limitation | Who fits is served | 1 | STS crane limiting |
| Policy 0 | Peak power limitation | Who fits is served | 1 | Balanced |
| Policy 1 | Peak power limitation | Who fits is served | Multiple | STS crane limiting |
| Policy 1 | Peak power limitation | Who fits is served | Multiple | Balanced |
| Policy 2 | Peak power limitation | Priority based | 1 | Balanced |
| Policy 3 | Peak power limitation | Priority based | Multiple | Balanced |

## 4.1. Policy 0

Policy 0 represents the least sophisticated policy in terms of intelligence. Its primary objective is to mitigate peak power consumption by imposing a peak power limitation based on the 'who fits is served' approach, as elaborated in Subsection 3.2.2. This policy does not incorporate any supplementary measures aimed at maintaining productivity under increasingly restrictive peak power limitations. Additionally, policy 0 exclusively permits the utilisation of a single kinematic profile, namely the conventional profile, as presented in Appendix B.2.

In advance of initiation any movement, the to be consumed power is estimated. Subsequently, it is checked whether the estimated power remains beneath the prescribed peak power limitation (Equation 3.1). If it is beneath the peak power limitation, the movement gets permission to start immediately. Conversely, if the estimated power surpasses the prescribed peak power limitation, the initiation of the movement is postponed with at least one second. After one second, the to be consumed power is again estimated and checked. Within this time period other equipment is allowed to make a request for power and to start a movement. The methodology of policy 0 is visualised in Figure 4.1.

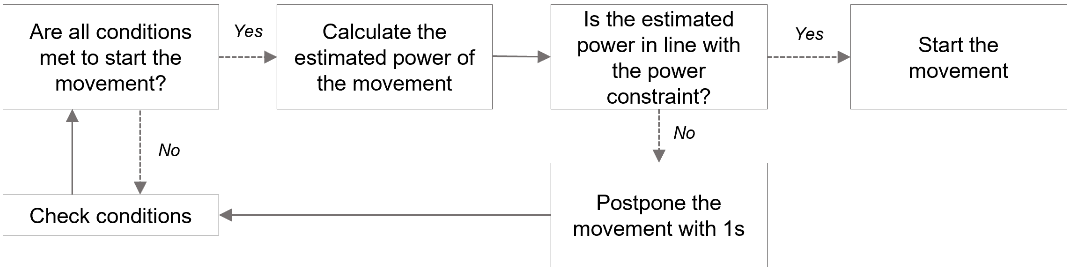



**Figure 4.1:** Representation of policy 0

### Verification

To ensure the proper implementation of policy 0 in the simulation model, two tests were conducted, each with a specific peak power limitation setting. The tests and their corresponding hypotheses are outlined below:

1. Test: peak power limitation set to 1000000 kW.
   Hypothesis: no requests for movements will be denied.
2. Test: peak power limitation set to 0 kW.
   Hypothesis: no movement will occur.

Both tests were executed, and the results confirmed the hypotheses. In test 1, no requests for movements were denied, indicating that the peak power limitation was not a constraint for any movement. In test 2, as expected, no movement took place due to the absence of available power. Based on the outcomes of these tests, it can be concluded that the simulation model successfully incorporates policy 0 and operates as intended under different peak power limitation scenarios.

## 4.2. Policy 1

Policy 1 aims to maintain the productivity under increasingly restrictive peak power limitations by allowing the application of adapted kinematic profiles. The working principle of policy 1 is visualised in Figure 4.2. The upper part of the flowchart is similar to the working principle of policy 0. At first it is check if the movement can start at the maximum values for acceleration, velocity and deceleration (the initial/conventional kinematic profile, Appendix B.2). If this initial kinematic profile satisfies the prescribed peak power limitation (Equation 3.1), the movement is granted permission to start immediately. However, if the kinematic profile violates the power constraint, an optimisation-embedded simulation is employed to determine near-optimal solution sets using a metaheuristic. In this optimisation-embedded simulation, the operations are simulated by the simulation model, and optimisation algorithms are triggered at specific points to make decisions regarding the to be applied kinematic profile [39]. The metaheuristic employed to find near-optimal solutions sets, containing an acceleration, a velocity, and a deceleration value, is a combination of Simulated Annealing and a Local Search heuristic, based on the study by Martin et al. [25]. The developed metaheuristic is able to explore and exploit the search space efficiently, enabling the identification of near-optimal solution sets that meet the power constraint while optimising the operational time of the specific movement.

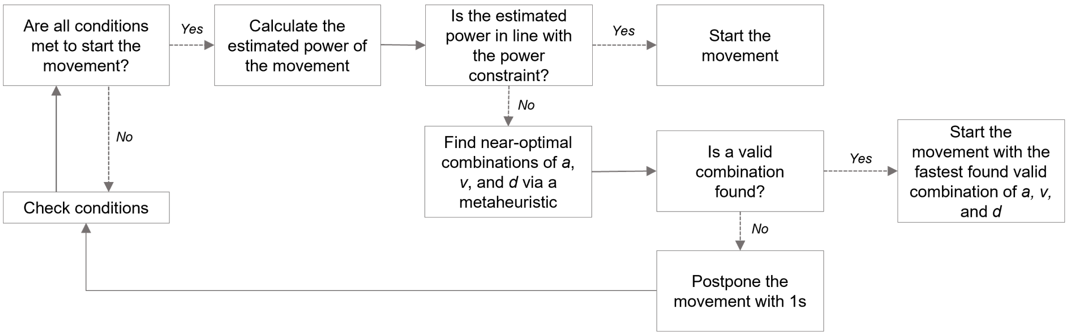



**Figure 4.2:** Representation of policy 1

The pseudocode of this metaheuristic is described in Figure 4.3. At first, several parameters are set. $P$ is the percentage accepted delay, $T_{initial}$ the initial temperature, $T_{stop}$ the stopping temperature, $a_{max}$, $v_{max}$, and $d_{max}$ are the maximum values for the acceleration, velocity, and deceleration. Secondly, the initial solution set is set, consisting of the maximum values for acceleration, velocity, and deceleration. Subsequently, the action time for the initial solution set is calculated ($t_{initial}$). If this kinematic profile is in line with the stated constraint in Equation 3.1, the executed solution set becomes the initial solution set. The executed solution set contains the values for acceleration, velocity, and deceleration at which the movement is going to be executed. Conversely, if this kinematic profile is not in line with the stated constraint, a Local Search over the initial solution set is done. Six new solutions sets are created: $\{a + 0.1, v, d\}$, $\{a - 0.1, v, d\}$, $\{a, v + 0.1, d\}$, $\{a, v - 0.1, d\}$, $\{a, v, d + 0.1\}$, and $\{a, v, d - 0.1\}$. In case the acceleration, velocity, or deceleration value is higher than the upper bound, the value is set to the corresponding upper bound. In case the acceleration, velocity, or deceleration value is smaller than 0.1, the value is set to 0.1. Thereafter, each created solution set is assessed on its validness. A solution set is valid if it is in line with both presented constraints. The first constraint implies that the operational time of the new found solution set ($t_{operational}$) must be below $t_{initial}$ plus a certain accepted delay (time constraint). The percentage accepted delay ($P$), is set to a value of 20% in this study. This value is found via an experiment, presented in Appendix E. The current solution set becomes, out of all valid created solution sets, the one with the lowest operational time ($t_{operational}$). If neither solution set is valid, the solution set with the lowest $t_{operational}$ is selected, furthermore its $t_{operational}$ value is increased by a thousand seconds. After a Local Search is conducted over the initial solution set a ‘kick’ is applied on the current solution set. The value of one randomly chosen variable in the current solution set is randomly changed to a value within the corresponding range. In case the acceleration, velocity, or deceleration value is higher than the upper bound, the value is set to the corresponding upper bound. In case the acceleration, velocity, or deceleration value is smaller than 0.1, the value is set to 0.1. A repetition of the code, explained above, is executed. With the Simulated Annealing metaheuristic it is decided whether the new solution set is accepted or not. As long as $T > T_{stop}$, a new ‘kick’ to the current solution set is executed. Conversely, if $T < T_{stop}$, an executed solution set is chosen. This executed solution set is a valid solution set that become a current solution set with the lowest value of $t_{operational}$.

### Verification

To evaluate if the implemented metaheuristic is working properly, the metaheuristic is verified according to two experiments. The first experiment aims to verify the behaviour of the metaheuristic by registering the number of applied adapted kinematic profiles under different peak power limitations. The experiment was conducted at balanced CT settings. The hypothesis was that the percentage of total applied adapted kinematic profiles would increase as the peak power limitation became more restrictive.

Four peak power limitations were considered: infinite kW (no power limitation), 4000 kW, 3000 kW, and 2000 kW. The results supported the hypothesis, as the percentage of total applied adapted kinematic profiles increased with increasingly restrictive peak power limitations. Specifically, under an infinite power limitation, 0% of the total applied profiles were adapted kinematic profiles. This percentage increased to 1% for a peak power limitation of 4000 kW, 5% for 3000 kW, and 23% for 2000 kW. These findings confirm the initial hypothesis and indicate that the metaheuristic appropriately responds to varying peak power limitations by increasing the utilisation of adapted kinematic profiles.

The second experiment aimed to assess the performance of the metaheuristic in finding near-optimal solution sets that adhere to the time constraint and power constraint (Equation E.2 and 3.1). A comparison was made between the near-optimal solution set obtained by the metaheuristic and the optimal solution set, which was obtained by exhaustively checking all possible solution sets.

Ten experiments were conducted for both the trolley and spreader movements. The total number of feasible solution sets for the trolley and spreader movements was 1200 and 1728, respectively. The near-optimal solution set found by the metaheuristic was evaluated based on its operational time and compared to the optimal solution set.

On average, the near-optimal solution set generated by the metaheuristic for trolley movements ranked in the top 0.62% of all solution sets, with a standard deviation of 0.57%. Similarly, for spreader movements, the near-optimal solution set ranked in the top 0.18% of all solution sets, with a standard deviation of 0.15%.

Additionally, the experiment verified whether a valid solution existed when the metaheuristic failed to find one. Ten new experiments were conducted for both trolley and spreader movements, specifically checking for the presence of a valid solution when the metaheuristic did not find one. Among the ten experiments for trolley movements where no valid solution was found by the metaheuristic, only in one case, one valid solution set was found by examining all possible solution sets. In all other cases, there was not a single valid solution set. For the ten experiments involving spreader movements, no valid solution set was found when checking all possible solution sets after the metaheuristic failed to find a valid solution.

These findings demonstrate the effectiveness of the metaheuristic in generating near-optimal solution sets within the time and power constraint, as it consistently ranked in the top percentile of solution sets. Additionally, the experiment confirmed that when the metaheuristic failed to find a valid solution, there were indeed no valid solution sets.

In terms of computational time, the metaheuristic performed impressively by providing near-optimal solutions within a blink of an eye. The computational time required by the metaheuristic was approximately less than half a second. On the other hand, the computational time needed to obtain the optimal solution set through exhaustive checking all possible solutions was significantly longer, taking approximately 2 to 5 seconds. Due to the high frequency of occurrence, this would have led to significant (undesired) higher simulation times per experiment. These findings demonstrate the effectiveness of the metaheuristic in generating near-optimal solution sets within the boundaries and

Set $P$, $T_{inital}$, $cooling\ rate$, $T_{stop}$, $a_{\max}$, $v_{\max}$, $d_{\max}$
Set the initial solution set $\{a_{\max}, v_{\max}, d_{\max}\}$

Determine $t_{inital}$

If $EP_i \leq PC - RP_i \; \forall\, i \in I$ then
    Executed solution set = initial solution set
    End of Method.
Else
    Compute a Local Search over the initial solution set by creating 6 new solution sets
    Determine $t_{operational}$ for each new solution set

    Loop for all new solution sets
        If $t_{operational} \leq t_{inital} * (1 + \frac{P}{100})$ AND $EP_i \leq PC - RP_i \; \forall\, i \in I$
            Solution set = valid
        Else
            Solution set = not valid

    Current solution set = of all the valid solution sets the one with the lowest $t_{operational}$

While $T > T_{stop}$
    Choose one variable of the current solution set randomly
    Change the value of this variable randomly within the ranges:
        a: [0.2, 0.3, …, $a_{upper\ bound} - 0.1$]
        v: [0.2, 0.3, …, $v_{upper\ bound} - 0.1$]
        d: [0.2, 0.3, …, $d_{upper\ bound} - 0.1$]
    Check if all values in the solution set are within the above stated ranges
    If not, change that value to the closest value within the specific range
    Compute a Local Search over the current solution set by creating 6 new solution sets (same as above)
    Determine $t_{operational}$ for each new solution set

    Loop for all new solution sets
        If $t_{operational} \leq t_{inital} * (1 + \frac{P}{100})$ AND $EP_i \leq PC - RP_i \; \forall\, i \in I$
            Solution set = valid
        Else
            Solution set = not valid

    New solution set = of all the valid solution sets the one with the lowest $t_{operational}$

    $delta = t_{operational,\ new\ solution\ set} - t_{operational,\ current\ solution\ set}$
    If $delta < 0$ OR $z\_uniform(1,0,1) < e^{\frac{-delta}{T}}$
        $Current\ solution\ set = New\ solution\ set$

    $T = T - cooling\ rate$

Executed solution set = of all the appeared valid current solution sets the one with the lowest $t_{operational}$

End of Method.

**Figure 4.3:** Pseudocode of the metaheuristic to find near-optimal solution sets

within a reasonable amount of time.

## 4.3. Policy 2

Policy 2 is developed to maintain productivity under increasingly restrictive peak power limitations, through the application of the 'priority based' approach. The objective of this approach is to utilise the waiting time of equipment. For instance, in the event of a confirmed saturation of the platform, the activation of the movements of the trolley-spreader combination towards the platform, occur solely in the absence of any higher-priority movements that are waiting for power. Herewith, the waiting time in front of the saturated platform is used as time to wait for power. The prioritisation mechanism in the 'priority based' approach ensures that power resources are allocated effectively and prevents unnecessary movement initiations when power availability is limited.

The working principle of policy 2 is visualised in Figure 4.4. In contrast to policy 1, the immediate calculation of the estimated power is replaced by the assignment of a priority number to the specific movement. This priority number is determined based on the presence or status of the corresponding interacting equipment. For example, if a trolley intends to move from the platform to the interchange point with the AGLV, it is assigned a low priority number if the AGLV is already at the interchange point, and a high priority number if the AGLV is not present. A low priority number signifies the importance of initiating the movement instantly regarding the productivity. Conversely, a high priority number indicates that there is no urgency to initiate the movement immediately. In terms of productivity, this movement can afford to wait, allowing movements with lower priority numbers to start as soon as possible.

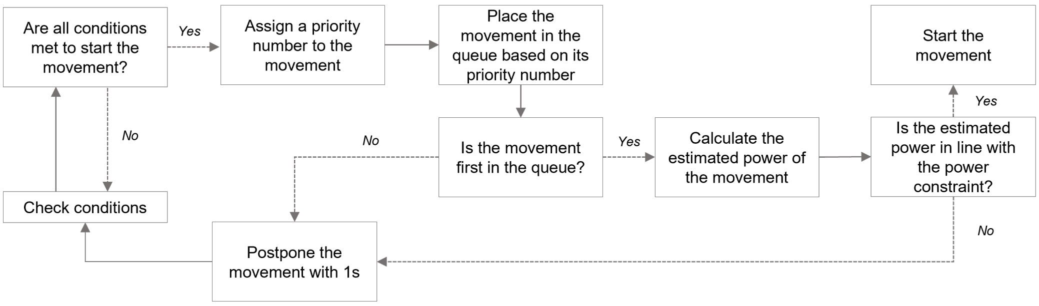



**Figure 4.4:** Representation of policy 2

After assigning a priority number to the movement, it is checked using Equation 4.1 if the priority number of the corresponding equipment ($PN_e$) is smaller than the priority numbers of all other equipment ($PN_k$) where $k$ represents the set of all equipment (except the corresponding equipment). If this is indeed the case, the estimated power demand is calculated and checked against the power constraint presented in Equation 3.1. If the estimated power demand is in line with the constraint, the movement is allowed to start immediately. However, if the estimated power demand exceeds the constraint, the movement is postponed by at least one second. Conversely, if the movement does not have the lowest priority number, it is postponed by at least one second. This cycle is repeated until the movement receives permission to start.

$$PN_e \ < \ PN_k \ \forall \ k \epsilon K \tag{4.1}$$

The assignment of priority numbers to the movements is predetermined based on specific criteria. These priority numbers depend on factors such as the type of operation being performed by the STS crane (loading or unloading), the specific trolley-spreader combination (landside or waterside), the movement, the presence of the interacting AGLV, and the status of the platform. The priority numbers assigned to the different cases in this study are provided in Appendix F.

#### Verification

To ensure the proper implementation of policy 2 in the simulation model, two test were conduced. The tests and their corresponding hypotheses are outlined below:

1. Test: set the priority number of a movement to infinity
   Hypothesis: when a movement is assigned a priority number of infinity, all other movements making requests will be prioritised over the specific movement. As a result, the specific movement will experience a significant delay in initiation.
2. Test: set the priority number of a movement to 0 while other movements are in the queue
   Hypothesis: when a movement is assigned a priority number of 0 (lowest possible), it will be prioritised over all the waiting movements. As a result, the specific movement is initiated promptly, as long as enough power is available.

Both tests were executed, and the results confirmed the hypotheses. In test 1, the specific movement experienced a significant delay in initiation. In test 2, as expected, the movement was initiated instantly, as long as enough power was available. It can be concluded that the simulation model successfully incorporates policy 2 and operates as intended.

## 4.4. Policy 3

Policy 3 is developed to maintain productivity under increasingly restrictive peak power limitations by combining policy 1 and policy 2. Herewith the strengths of both policies are utilised. The working principle of policy 3 is visualised in Figure 4.5.

The first part of the working principle of policy 3 is a reproduction of policy 2. At the moment the movement has priority to start, but not enough power is available, policy 1 is introduced. According to the metaheuristic, described in Section 4.2, near-optimal combinations of acceleration, velocity and deceleration are found. If one or more valid solutions are found, the fastest valid solution is selected and executed. If not, the movement is postponed with at least one second. This cycle is repeated until the movement receives permission to start.

#### Verification

Policy 3, is a merge of policy 1 and policy 2. Therefore, the verification tests conducted for policy 1 and policy 2 also apply to policy 3. No additional verification tests specific to policy 3 were conducted in this study.

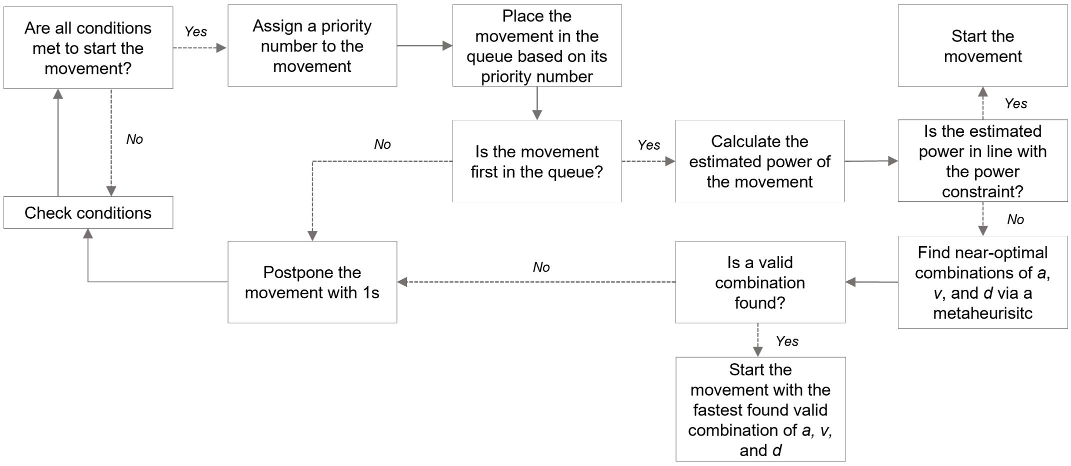



**Figure 4.5:** Representation of policy 3


# 5. Results

This chapter evaluates the operational and economic impact of the developed policies outlined in Chapter 4. The operational impact is assessed through an analysis of the average productivity (handled boxes per hour) of the STS cranes and the economic impact through analysing to what extend the yearly contractual power demand related costs can be reduced without impacting the productivity. Firstly, in Section 5.1, the discrepancy in productivity decline under increasingly restrictive peak power limitations is analysed for policy 0, for different CT settings. Section 5.2 provides insight into the effect of the policies on the STS cranes' productivity under increasingly restrictive peak power limitations. Additionally, the economic impact of the policies is analysed in Section 5.3.

For each policy, a total of 18 scenarios are analysed, each featuring a unique peak power limitation. The base scenario has no peak power limitation (the power limit is infinite). Subsequently, the peak power limitation is reduced in increments of 2000 kW from an initial level of 4800 kW. The peak power of a single STS crane occurs when hoisting a 40-ton container, requiring 1954 kW. Scenarios with peak power limitations below this level are expected to report a relatively low productivity for policies that do not allow an adapted kinematic profile. Because, attempting to hoist a 40-ton container while a peak power limitation below 1954 kW is applied, would lead to the rejection of the movement and the shutdown of the specific STS crane. The lowest applied peak power limitation is set at 1600 kW, which allows for the verification of the aforementioned situation.

## 5.1. Container Terminal Setting vs. Productivity Decline

As described in Section 3.1.2, the evaluation of policy 0 and policy 1 in this study considers two different CT settings. In the first setting, referred to as balanced settings, the number of AGLVs and RMG stacks is balanced in relation to the cluster of STS cranes. In the second setting, referred to as the STS crane limiting setting, the cluster of STS cranes is the limiting factor in the overall productivity of the CT. The decline in the average productivity per STS crane, resulting from the application of a peak power limitation, is illustrated in Figure 5.1 for both CT settings. The percentile decrease in the productivity for increasingly restrictive peak power limitations is relatively smaller at balanced CT settings.

The discrepancy in the productivity decline between the two settings can be attributed to the specific configuration of the CT. At STS crane limiting settings, the STS crane typically does not have to wait for an AGLV to arrive. Therefore, any delay in the initiation of a movement, due to insufficient

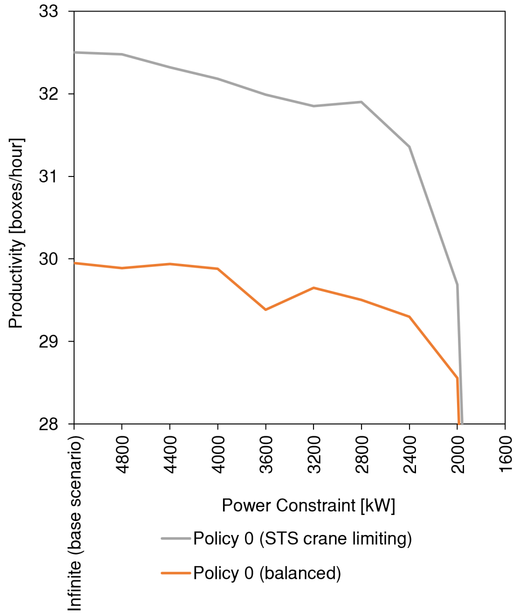



**Figure 5.1:** Productivity decline under increasingly restrictive peak power limitations, for different CT settings

power availability, directly impacts the STS crane's productivity. On the other hand, at balanced CT settings, there is a possibility that the STS has to wait for an AGLV to arrive. In this case, any delay in the initiation of a movement, due to insufficient power availability, does not directly impact the STS cranes' productivity. It can be stated that the specific configuration of the CT plays a crucial role in determining the direct impact of applying a peak power limitation on the STS cranes' productivity. It highlights the importance of considering the layout and equipment of the CT when assessing the impact.

## 5.2. Operational Impact of the Policies

This section aims to asses the operational impact of the different policies, by analysing key figures. Additional relevant figures and data can be found in Appendix G. Figure 5.2 presents the discrepancy in the productivity decline across all the developed policies. The decline for each policy is extensively discussed in the Subsections 5.2.1, 5.2.1, 5.2.1, and 5.2.1 for policy 0, policy 1, policy 2, and policy 3, respectively.

Policy 2 and policy 3 have the objective of maintaining productivity under increasingly restrictive peak power limitations by utilising the 'known' waiting time as an opportunity to wait for available power or to keep power available for urgent movements that directly impact the productivity. The 'known' waiting time is the time spent waiting for certain conditions to be met, before finishing the specific movement. In the case of the waterside trolley-spreader combination, it may need to wait in front of a fully loaded platform or for the landside trolley-spreader combination to vacate the platform. Conversely, the landside trolley-spreader combination might need to wait for the waterside trolley-spreader combination to vacate the platform, in front of a fully loaded platform, or for an AGLV to arrive. The relationship between the policies and the waiting time for all peak power limitations is illustrated in Figure 5.3. It is important to note that the waiting time referred to in the figure, does not include the time required to wait for power at the beginning of a movement.

In general, several observations regarding the waiting times can be made. At first, it is observed

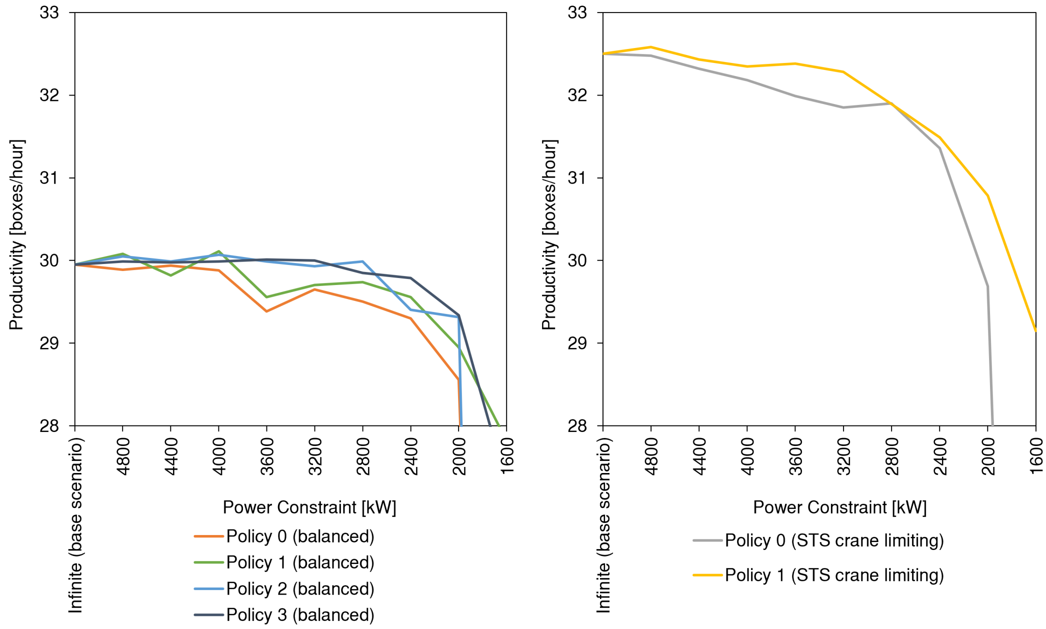



**Figure 5.2:** Decline in the productivity under increasingly restrictive peak power limitations

that the landside trolley-spreader combination experiences more waiting time compared to the waterside trolley-spreader combination. This disparity can be explained by the operational differences between the two trolley-spreader combinations. The waterside trolley-spreader combination transfers containers between the vessel and the platform, and therefore, it may only need to wait in front of the platform. On the other hand, the landside trolley-spreader combination is responsible for transferring containers between the platform and the AGLVs. As a result, the landside trolley-spreader combination may need to wait both in front of the platform and for an AGLV to arrive, leading to longer waiting times overall.

Secondly, for most policies at both settings, the trolley-spreader combinations exhibit a consistent decrease in the observed waiting time for increasingly restrictive peak power limitations. However, it is noteworthy that the waterside trolley-spreader combination shows an increase in the waiting time for peak power limitations below 2000 kW for policies that do not allow adapted kinematic profiles (policy 0 and policy 2).

The observed consistent decline in waiting time for the trolley-spreader combinations under increasingly restrictive peak power limitations can be attributed to the increased number of denied power requests, as depicted in Figures G.6 and G.7. When a power request is denied, the equipment is unable to initiate its planned movement and must wait for power (this waiting time for power is not included in the waiting time presented in Figure 5.3). This waiting period raises the opportunity for the AGLV to arrive or for the other spreader-trolley combination to clear or stack the platform, resulting in reduced waiting times for the trolley-spreader combination once the specific movement is granted permission to start. On the other hand, if a trolley-spreader combination intends to move away from the platform, but its request is denied, it will block the platform, leading to an increase in the waiting time of the other trolley-spreader combination attempting to reach the platform. However, based on the observed waiting times this occasion does not occur frequently to have a dominant impact on the waiting times.

The peak in waiting time for the waterside trolley-spreader combination, under policy 0 and policy 2, observed for peak power limitations below 2000 kW, can be attributed to the significant in-

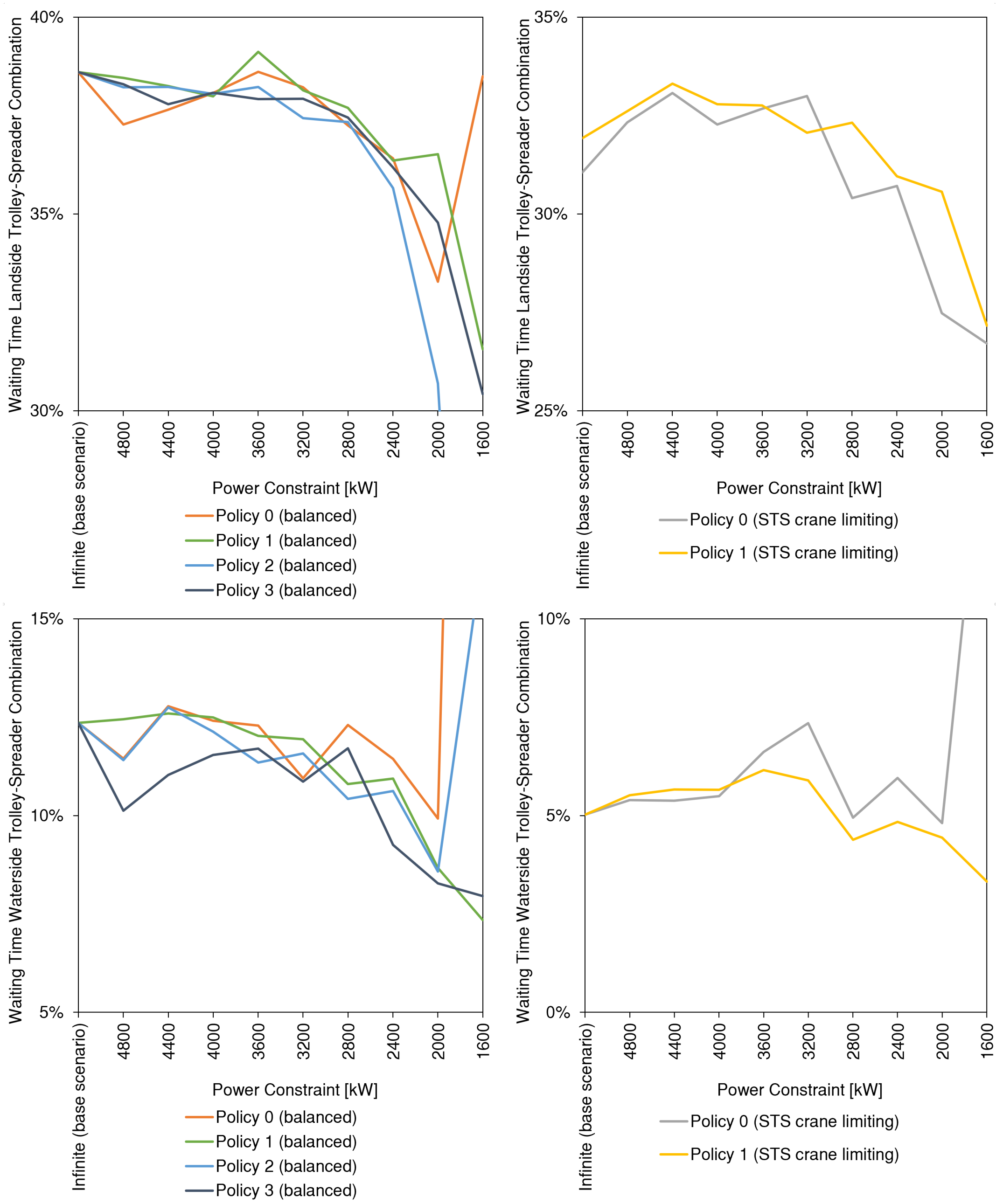



**Figure 5.3:** Percentile waiting time for both the landside and waterside trolley-spreader combination

crease in power request denials from the landside spreader, as illustrated in Figure G.6. When the landside spreader is unable to initiate its movement due to power limitations, it has to wait for power (which is not included in the waiting time calculation). As a result, the waterside trolley-spreader combination may need to wait longer to pick or place a container on the platform, since the landside trolley-spreader combination might block the platform, not empty the platform, or not stack the platform.

Lastly, the steep increase in the denial of power requests for peak power limitations below 2000 kW for both the landside and waterside spreader (as shown in Figures G.6 and G.7) under policy 0 and policy 3, leads to a decrease in the total number of requests from the corresponding trolley. Because the conditions necessary for the trolley movement are not fulfilled as the corresponding spreader movement is not initiated. According to the data, this relates to less denied power requests from the trolley.

### 5.2.1. Productivity Policy 0

Policy 0 aims to reduce the peak power by limiting the power demand according to the 'who fits is served' approach. No incentives are applied to maintain productivity for increasingly restrictive peak power limitations. Policy 0, therefore, operates as a benchmark policy in terms of productivity degradation for increasingly restrictive peak power limitations. As illustrated with an orange line in Figure 5.2 for balanced CT settings and with a grey line for STS crane limiting CT settings, a significant decline in the productivity is observed when the peak power limitation is set below 3800 kW for both settings. This decline clearly demonstrates the significant impact that increasingly restrictive peak power limitations have on the productivity under policy 0. Additionally, the productivity massively declines when the peak power limitation is set below 2000 kW. This sharp drop can be attributed to the shutdown of certain STS cranes that are attempting to hoist the heaviest containers, as mentioned in the introduction of this chapter.

The observed increase in waiting time for the landside trolley-spreader combination at balanced CT settings in policy 0 stands out when compared to the waiting time for the landside trolley-spreader combination at STS crane limiting settings for policy 0, and the waiting time for the landside trolley-spreader combination at balanced CT settings for policy 2. This discrepancy can be attributed to the significantly lower average STS crane productivity reported at a peak power limitation of 1600 kW for policy 0 at balanced CT settings.

### 5.2.2. Productivity Policy 1

Policy 1 aims to mitigate the impact of increasingly restrictive peak power limitations on the productivity, by allowing the application of adapted kinematic profiles, while meeting the power and time constraints presented by Equations 3.1 and E.2, respectively. Similar to policy 0, policy 1 also follows the 'who fits is served' approach. For both CT settings the analysis reveals that policy 1 exhibits a similar pattern of productivity decline as policy 0 at both settings. However, there are notable differences between the two policies.

Firstly, the productivity under policy 1, represented by the green line at balanced CT settings and by the yellow line at STS crane limiting CT settings, in Figure 5.2, is in most scenarios slightly higher than the productivity under policy 0. This indicates that the application of adapted kinematic profiles helps to keep up the productivity slightly compared to policy 0 under increasingly restrictive peak power limitations.

Secondly, the less steep decline in the productivity for peak power limitations below 2000 kW, for both CT settings, can be attributed to the allowance of adapted kinematic profiles. Equipment handling the heaviest containers have, due to the allowance of adapted kinematic profiles, the ability to handle them promptly or within a reasonable time period. Moreover, for the same reasoning, the waiting times depicted in Figure 5.3 for policy 1 do not exhibit an increase for peak power limitations below 2000 kW but rather a decrease.

Moreover, Figure 5.3 reveals that the waiting time experienced by the landside trolley-spreader combination under policy 1 is slightly higher compared to policy 0, for both settings. Conversely, the waiting time for the waterside trolley-spreader combination under policy 1 is slightly lower compared to policy 0, for both settings. This suggests that the waterside trolley-spreader combination experiences reduced waiting time in front of the platform. There are two possible causes for this, either the landside trolley-spreader combination operates faster due to the allowance of adapted kinematic profiles, or the experienced increase in the operational time when an adapted kinematic profile is applied on the waterside trolley-spreader combination leads to reduced waiting times in front of the platform.

Additionally, Figures G.6 and G.7 show a reduction in the denied power request under policy 1 compared to policy 0. Furthermore, a notable finding is that the percentage decrease in denied power request between policy 0 and policy 1, is higher for the trolley movements in comparison to the spreader movements. This suggests that the trolley movements benefit the most from the allowance of adapted kinematic profiles.

Lastly, Figure G.5 demonstrates an increasing trend in the application of adapted kinematic profiles for increasingly restrictive peak power limitations. It is observed that the utilisation of applying adapted kinematic profiles, initiates when the peak power limitation is set below 4400 kW, at both CT settings. Furthermore, Figure G.3 illustrates that the discrepancy between the set peak power limitation and the observed peak power is consistently smaller for policy 1 in comparison to policy 0. Additionally, Figure G.4 illustrates that the power distribution for policy 1 exhibits a slight shift towards higher power values compared to policy 0, indicating that movements are initiated using adapted kinematic profiles that closely match the set peak power limitation. These observations align with the intended purpose of the policy.

### 5.2.3. Productivity Policy 2

Policy 2 aims to mitigate the impact of increasingly restrictive peak power limitations on the productivity through the application of a 'priority based' approach. The objective of this approach is to utilise 'known' waiting times as an opportunity to wait for available power or to keep power available for urgent movements that directly impact the productivity, as described in the introduction of this chapter. In Figure 5.2, it can be observed that policy 2 demonstrates a relatively stable and consistent productivity under increasingly restrictive peak power limitations till 2800 kW. This indicates that policy 2 is effective in maintaining a high level of productivity for these peak power limitations. However, once the peak power limitation is set below 2800 kW, there is a significant decline in productivity visible for policy 2. Despite this decline, policy 2 still outperforms policy 0 in terms of productivity for peak power limitations higher than 2000 kW. Eventually, the productivity for policy 2 exhibits a substantial decrease when the peak power limitation is set below 2000 kW, resembling the behaviour observed under policy 0.

Similar to policy 0, the waiting time for the waterside trolley-spreader combination increase significantly for peak power limitations below 2000 kW. This can be attributed to the steep increase of denied power requests of the landside spreader, as depicted in Figure G.6. As described in the introduction of this chapter, the opposite trolley-spreader combination will therefore experience extreme high waiting times.

Figure 5.3 shows a decrease in the observed waiting times for both the landside and waterside trolley-spreader combination compared to the ‘who fits is served’ policies. This indicates that when movements are initiated, they are more likely to be completed without waiting in front of the platform or for an AGLV to arrive. This suggests that the initiation of non-urgent movements, of which it is known that they are likely to experience waiting time, are appropriately delayed, ensuring power availability for urgent movements.

As illustrated in the Figures G.6 and G.7, the percentage of denied power requests is slightly lower compared to policy 0. It is important to note that power requests are made only when the corresponding movement has priority to start. However, the data still indicates that when a power request is made, it is more likely to be accepted compared to policy 0. All observations suggest that the available power is effectively allocated to the most urgent movements that directly impact the productivity.

### 5.2.4. Productivity Policy 3

Policy 3 aims to maintain productivity under increasingly restrictive peak power limitations by combining policy 1 with policy 2. Policy 3 demonstrates a relatively stable and consisted productivity for peak power limitations up to 2600 kW. This indicates that policy 3 is effective in maintaining a high level of productivity for these peak power limitations. A massive decline in the productivity is visible for peak power limitations of 2000 kW and below. However, similar to policy 1, a less steep decline in the productivity for peak power limitations below 2000 kW is visible compared to policy 0. This can be attributed to the allowance of adapted kinematic profiles as described in Subsection 5.2.2.

Figure 5.3 reveals that only the waterside trolley-spreader combination exhibits a significant reduction in the waiting time compared to policy 0. In addition to the previously mentioned causes in Subsection 5.2.2, another possible factor contributing to this reduction could be the cautious approach of the waterside trolley-spreader combination. The specific equipment may only initiate a movement towards the platform when no other equipment has a higher priority. As a result, it is likely that the specific equipment can move immediately towards the platform once permission is granted.

Furthermore, Figures G.6 and G.7 show a reduction in denied power requests under policy 3 compared to policy 0. This suggests that the available power is effectively allocated to the most urgent movements and these movements are likely to be directly initiated by either the initial kinematic profile or an adapted kinematic profile.

Moreover, similar to policy 1, Figure G.5 shows an increasing trend in the application of adapted kinematic profiles under increasingly restrictive peak power limitations. However, it is observed that policy 3 makes slightly less use of adapted kinematic profiles compared to policy 1. This can be attributed to the fact that policy 3 prioritises keeping power available for urgent movements by minimising the initiation of non-urgent movements. As a result, when a movement requests power under policy 3, it is more likely that sufficient power is available, reducing the need for adapted kinematic profiles. Furthermore, similar to policy 1, Figure G.3 illustrates that the discrepancy between the applied peak power limitation and the observed peak power is consistently smaller for policy 3 compared to policy 0. Indicating that movements are initiated using adapted kinematic profiles that closely match the applied peak power limitation. These observations align with the intended purpose of the policy.

## 5.3. Economic Impact of the Policies

The economic impact of the policies is assessed by evaluating the greatest percentage decrease in contractual power demand related expenses that can be achieved per policy while maintaining productivity. For every policy a critical peak power limitation is identified beyond which productivity is negatively impacted. At this critical peak power limitation, maximum contractual power demand related cost savings can be achieved while ensuring that productivity remains unharmed, in comparison to the base scenario without the application of a peak power limitation. Figure 5.4 presents the critical peak power limitations associated with each policy, along with the potential corresponding percentage reduction in the contractual power demand related expenses.

At balanced CT settings, the critical peak power limitations for policy 0, policy 1, policy 2, and policy 3 are 3800 kW, 4000 kW, 2800 kW, and 2600 kW, respectively. Policy 2 and policy 3, in which the peak power limitation is implemented according to the 'priority based' approach, demonstrate the lowest critical peak power limitation values. As a result, significant reductions in the contractual power demand related expenses can be attained of 49% under policy 2 and 53% under policy 3.

Policy 0 and policy 1, when operating at balanced CT settings, exhibit higher critical peak power limitations, leading to comparatively lower cost savings in terms of contractual power demand related costs of 31% under policy 0 and 28% under policy 1. At STS crane limiting settings, the costs savings slightly increase due to the higher observed peak power demand in the base scenario and due to a lower critical peak power limitation for policy 1. At these settings policy 0 achieves cost savings of 34% and policy 1 of 41%.

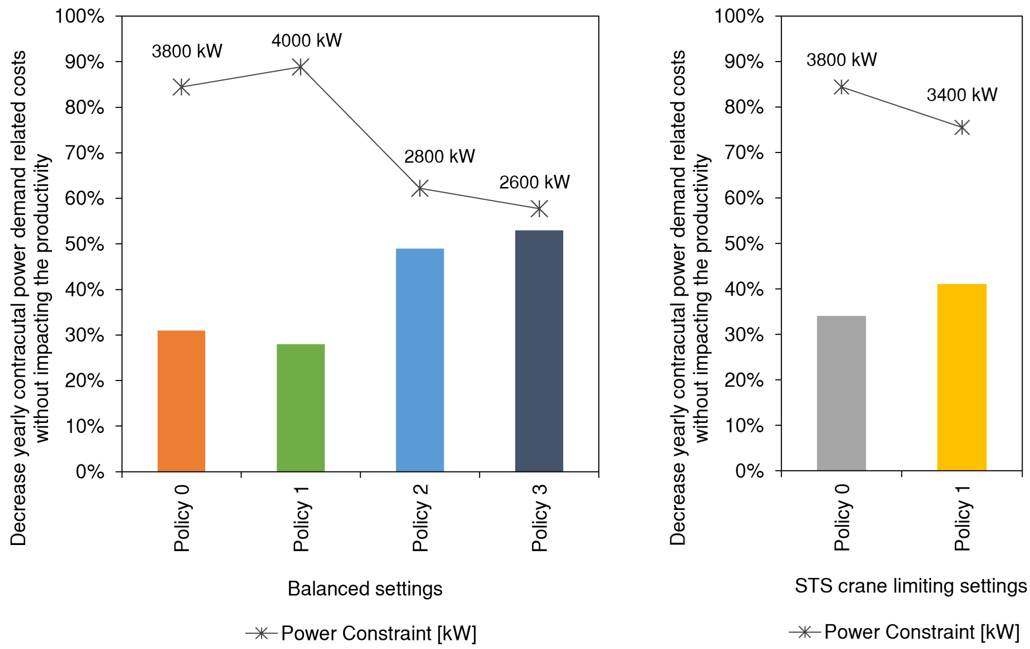



**Figure 5.4:** Maximum contractual power demand related cost savings without negatively impacting the productivity

Photo: Peakpx

# 6. Discussion

This study aimed to develop operational policies for maintaining the productivity of a cluster of STS cranes under increasingly restrictive peak power limitations. To achieve this objective, four operational policies were developed and subsequently evaluated. The impacts of these policies were examined through a discrete event simulation model and presented in Chapter 5.

The key findings resulting from this study are thoroughly discussed in Section 6.1. A detailed comparison between the findings of this study and the research conducted by Geerlinges et al. [10] is presented in Section 6.2. Despite the valuable insights provided by this study, it is important to acknowledge the presence of certain limitations, which are discussed in Section 6.3. Finally, Section 6.4 offers several recommendations for future research directions.

## 6.1. Key Findings

The implementation of a peak power limitation is an effective strategy to reduce the peak power demand of a cluster of six STS cranes. With the implementation of a peak power limitation on a cluster of STS cranes less transport capacity has to be reserved by the grid operator for the specific CT, resulting directly into a decrease in the contractual power demand related costs. Nonetheless, notable variations in effectiveness are observed among the evaluated policies. Furthermore, the effectiveness of the policies also vary across different CT settings.

At first, as outlined in Section 5.1, the ability to maintain productivity under increasingly restrictive peak power limitations varies across different CT settings. At STS crane limiting CT settings the productivity decline is more aggressive compared to balanced CT settings. This observation can be attributed to the direct influence, the waiting time for power has, on the STS crane's productivity at STS crane limiting CT settings.

Secondly, the results indicate that the 'priority based' approach policies (policy 2 and policy 3) outperform the 'who fits is served' approach policies (policy 0 and policy 1) for peak power limitations greater than 2000 kW in terms of productivity. Their ability to maintain productivity stands out for the, in this study, medium range peak power limitations, ranging from 4000 kW to 2800 kW. These observations suggest that the available power in the 'priority based' approach policies is effectively allocated to the most urgent movements that directly impact the productivity.

Furthermore, for the 'who fits is served' approach policies, the allowance of adapted kinematic profiles improves the productivity for almost all peak power limitations at both CT settings. While, for the ‘priority based’ approach policies, the allowance of adapted kinematic profiles positively impacts the productivity solely for peak power limitations below 2800 kW. This can be attributed to the fact that the productivity decline under policy 2 starts below this peak power limitation.

In general, it can be stated that policy 3, which combines a ‘priority based’ approach with the utilisation of adapted kinematic profiles, demonstrates the best performance in maintaining productivity under increasingly restrictive peak power limitations. The observed productivity patterns of policy 1 and policy 2 indicate that the productivity achieved under policy 3 for peak power limitations above 2800 kW can be primarily attributed to the implemented ‘priority based’ approach (policy 2). However, for peak power limitations below 2800 kW, the combined strengths of both the ‘priority based’ approach (policy 2) and the allowance for adapted kinematic profiles (policy 1) are utilised to maintain a satisfactory level of productivity. Consequently, the implementation of policy 3 therefore leads to the most contractual power demand related costs savings without impacting the productivity. By applying a peak power limitation of 2600 kW according to policy 3, 53% of the contractual power demand related costs can be reduced compared to the base scenario.

## 6.2. Comparison to Geerlings et al.

The implementation of a peak power limitation as a peak shaving strategy was originally proposed by Geerlings et al. [10]. They applied a collective peak power limitation on an entire CT using the ‘first come first serve’ approach. In case of power unavailability, only the movements of STS cranes were postponed. Due to differences in study design, direct comparisons between the findings of this study and the work conducted by Geerlings et al. [10] are not feasible, however some meaningful comparisons can still be made.

The productivity decline for a cluster of six ship-to-shore STS cranes under increasingly restrictive peak power limitations, as reported by Geerlings et al. [10], is presented in Figure 6.1. It is important to note that the data presented in Figure 6.1 is achieved by reconstructing the data reported by Geerlings et al. [10]. None of the developed policies in this study is an exact replication of the approach used by Geerlings et al. [10], however policy 0 at STS crane limiting CT settings comes closest to their work. Therefore, the productivity decline reported by Geerlings et al. [10] is compared to the productivity decline observed under Policy 0 at STS crane limiting CT settings.

Several differences can be observed from Figure 6.1. Firstly, the productivity reported by Geerlings et al. [10] is significant higher. This can be attributed to the setup of the simulation model of Geerlings et al. [10], in which the STS cranes never have to wait for an AGLV to arrive, whereas in the model of this study it is likely that the STS does not have to wait for an AGLV to arrive but it is not guaranteed. Secondly, although a similar pattern is observed for the productivity decline, the productivity reported by Geerlings et al. [10] is adversely impacted by more than one percent for peak power limitations below 3400 kW while for policy 0, this decline already occurs at a peak power limitation of 3800 kW. Furthermore, the decline reported by Geerlings et al. [10] is less steep compared to policy 0. This discrepancy is not in line with the ‘first come first serve’ approach reported by Geerlings et al. [10], which would suggest a more steeper decline in the productivity, as other STS cranes would have to wait when one of the heaviest containers needs to be hoisted. The less steep decline can be attributed to the difference in the container weight distribution, as illustrated in Figure 6.1. In Geerlings et al.’s [10] model, relatively light containers are handled, resulting in a lower overall power demand of the STS crane movements, leading to a less steep decline in the reported productivity for increasingly restrictive peak power limitations.

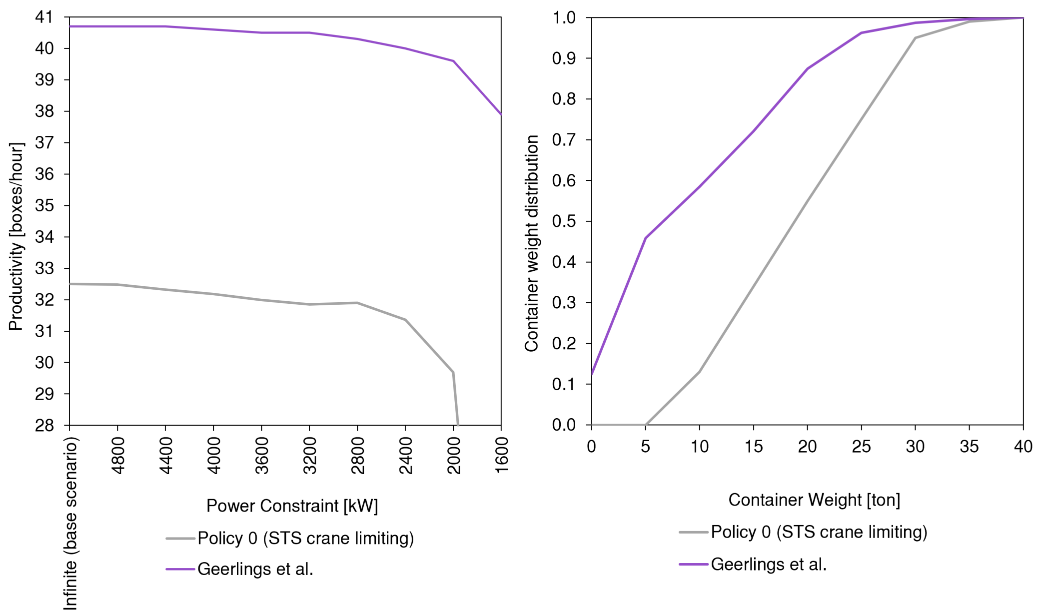



**Figure 6.1:** Comparison between policy 0 at STS crane limiting CT settings and Geerlinges et al. [10]

## 6.3. Limitations

This study offers insightful information on the possibility of peak shaving the power demand of a cluster of STS cranes while preserving productivity. However, it is important to acknowledge its limitations in order to maintain credibility and provide an accurate understanding of the conclusions that can be drawn.

Firstly, it is important to acknowledge that this study was constrained by computational limitations, resulting in a restricted number of replications per experiment. Increasing the number of replications would have potentially enhanced the reliability and robustness of the study outcomes.

Secondly, the investigation was focused solely on a cluster of six dual trolley STS cranes. While these cranes are widely used in CTs, the findings may not be directly applicable to other types of cranes or different cluster sizes. Therefore, the generalizability of the results to a broader context should be interpreted with caution.

Furthermore, the contractual power demand related costs in this study are based on the fee charged by the Dutch gird operator Stedin. It should be noted that these charges can vary among different grid operators worldwide and change every year. Therefore, caution should be exercised when interpreting the cost savings associated with the reduction of the set contractual power demand, and a thorough re-evaluation is recommend for each specific situation.

Despite the acknowledged limitations, the results of this study remain valid in addressing the research question and contributing to the understanding of the operational and economic impact of the developed policies. By presenting these limitations, readers are informed about the need for caution when drawing conclusions based on the presented results in different contextual settings.

## 6.4. Recommendations for Future Research

Based on the study conduced, several recommendations for future research are identified:

I. *Analysis of a single trolley STS.* This study focuses on a dual trolley STS cranes performing single movements. However, investigating the productivity decline for a single trolley STS crane would be insightful, particularly regarding the performance of the 'priority based' approach in the absence of a platform.

*II. Validation with different cluster sizes* This study considers a cluster of six STS cranes. To validate the obtained results, it would be valuable to explore the impact of the developed policies on the productivity by adapting the cluster size.

*III. Split cluster of STS cranes each having a own peak power limitation* The current study applies a collective peak power limitation to a cluster of six STS cranes, potentially causing one crane to block the others. Investigating the scenario where the cluster is split into smaller groups, each with its own peak power limitation, would be particularly interesting for larger cluster sizes.

*IV. Productivity decline for double cycling* The current study focuses on the productivity decline, for different policies, under increasingly restrictive peak power limitations during either loading or unloading operations. Exploring the impact of the developed policies on the productivity when double cycling is employed would provide valuable insights.

*V. Multiple acceleration/velocity/deceleration values in one move* Policy 1 and policy 3 allow the application of adapted kinematic profiles, however, only one acceleration, velocity, and deceleration value is picked. Investigating whether the productivity decline under these policies can be mitigated by employing multiple values for acceleration, velocity, or deceleration would be an intriguing avenue for future research.

*VI. Adapt kinematic profile based on the AGLV arrival time* In this study no policies are developed in which the kinematic profile is adapted on the arrival time of the corresponding AGLV. Assessing whether adapting the kinematic profile in this manner can smooth the power demand and reduce the productivity decline under increasingly restrictive peak power limitations would be a valuable investigation.

*VII. Inclusion of additional equipment* This study focuses on controlling the power demand of STS cranes, while a CT comprises out of various electrified equipment. Investigating the impact of a collective peak power limitation, according to the approaches investigated in this study, that include other equipment would be an interesting expansion to this study.

Photo: Peakpx

# 7. Conclusion

As outlined in Chapter 1, the grid operator allocates a specific amount of transport capacity to each consumer based on the expected highest required power demand at any moment by the consumer. The reserved transport capacity is charged by the grid operator, referred to as contractual power demand related costs. STS cranes are, due to their volatile and substantial power demand, one of the primary contributors to the required transport capacity and the associated contractual power demand related costs in a CT. However, since extreme high power demand values occur infrequently, the reserved transport capacity is only utilised a few times per year. Without applying operational policies, the load factor (average power divided by the peak power) of a cluster of six STS cranes at balanced and STS limiting settings was found to be 0.21 and 0.22, respectively, indicating inefficient use of the available transport capacity. Consequently, the CT operator incurs significant expenses for a resource that is rarely utilised.

The analysis presented in Section 2.5 highlights that the infrequent occurrence of the highest observed power demands of a cluster of six STS cranes supports the notion that applying a peak power limitation to eliminate these extreme values will not directly adversely affect the productivity of the STS crane. By reducing the required peak power through the implementation of such a limitation, the necessary transport capacity is also reduced, resulting in a decrease in the contractual power demand related costs. The level of savings in contractual power demand related costs is directly influenced by the stringency of the peak power limitation, with more restrictive limitations yielding greater savings. However, at a certain peak power limitation, the productivity will be adversely impacted, leading to unfavourable additional handling time and an increase in handling costs, which has led to the following research objective:

> "*Developing operational policies that effectively maintain productivity for a cluster of STS cranes under increasingly restrictive peak power limitations*"

Consequently, based on the aforementioned research objective, four operational policies were formulated as part of this study. The assessment of these policies required their evaluation across various scenarios and key parameters. As indicated, the implementation of a peak power limitation is deemed economically viable, provided that the productivity is maintained. Achieving a harmonious equilibrium between the operational and economic impact is therefore crucial, which has led to the following formulation of the research question:

> "*What is the operational and economic impact of the developed operational policies,*

*aimed at maintaining productivity for a cluster of six STS cranes under increasingly restrictive peak power limitations?*"

The answer to this research question and the main findings of this study are presented and summarised in Section 7.1. The contributions made to the literature and the CT industry are outlined in Section 7.2.

## 7.1. Answer to the Research Question

The answer to the research question can be divided into the operational and economic impact. By analysing the outcomes presented in Chapter 5, numerous conclusions can be drawn concerning the operational and economic effects of the investigated policies, which aim to maintain productivity under increasingly restrictive peak power limitations. In this section, the operational impact is examined first, followed by the evaluation of the economic impact. Ultimately, a comprehensive recommendation is proposed considering the observed operational and economic impact of the policies.

### Operational Impact

The peak power limitations can be categorised into three ranges, as determined by the results analysis: (1) infinite-4000 kW, (2) 3600-2800 kW, and (3) 2400-1600 kW, hereafter referred to as high, medium, and low peak power limitations, respectively. For high peak power limitations, the policies do not significantly differ from one another. However, for most peak power limitations within this range, policy 1, policy 2, and policy 3 slightly outperform policy 0 in terms of productivity.

Within the medium peak power limitation range, the policies employing the 'priority based' approach (policy 2 and policy 3) demonstrate superior performance compared to the policies based on the 'who fits is served' approach. The 'priority based' approach policies do not experience any decline in the productivity, resulting in zero operational impact caused by the applied peak power limitation. The difference between the approaches can be attributed to the proper allocation of the available power to the most urgent movements that directly impact the productivity by the 'priority based' approach. In this specific range, the application of adapted kinematic profiles has a greater positive impact on the productivity for the 'who fits is served' approach compared to the 'priority based' approach.

At the lowest peak power limitations, productivity is significantly impacted. While policy 3 manages to maintain satisfactory productivity levels for the higher end of this range, it also experiences a decline in the productivity as the peak power limitation is set to 2000 kW and below. The ability of policy 3 to maintain a satisfactory level of productivity at the higher end of this range can be attributed to the allowance of adapted kinematic profiles. In this specific range, the application of adapted kinematic profiles has a positive impact on the productivity of both the 'who fits is served' and 'priority based' approach.

### Economical Impact

The reduction in the collective peak power demand of a cluster of STS cranes, while maintaining productivity, yields direct economic advantages. This favourable outcome arises primarily from the diminished expenses associated with the contractual power demand, while other operational costs remain unchanged. Based on the obtained results, it can be concluded that the implementation of a peak power limitation of 2600 kW, following the 'priority based' approach, in conjunction with the adoption of adapted kinematic profiles (policy 3), leads to the most cost savings without adversely impacting the productivity. By a peak power limitation of 2600 kW according to policy 3, 53% of the contractual power demand related costs can be reduced compared to the base scenario. However, without the adoption of adapted kinematic profiles (policy 2), a satisfactory reduction of 49% is achieved. The 'who fits is served' approach policies without (policy 0) and with the adoption of adapted kinematic profiles (policy 1) lead to a less decrease in the contractual power demand related costs of 31% and 28% at balanced CT settings and of 34% and 41% at STS crane limiting settings, respectively.

#### Recommendation based on the observed Operational and Economical Impact

Given that the results of this study were obtained under computational limitations and therefore with a limited number of replications, it is important to note that a general recommendation can be made while acknowledging the need for further replications to strengthen the findings. The results clearly indicate, for balanced CT settings, that the developed 'priority based' approach, in comparison to the 'who fits is served' approach, is more effective in maintaining productivity under increasingly restrictive peak power limitations and therefore able to achieve the most cost savings. Additionally, when combined with adapted kinematic profiles, the 'priority based' approach (policy 3) exhibits the best performance in terms of operational and economic impact. As a result, policy 3 is recommended to be implemented to reduce the collective peak power of a cluster of six STS cranes. It can reduce the yearly contractual power demand related costs by 53% in comparison to the base scenario, which is the greatest recorded reduction of all created policies without affecting the productivity.

## 7.2. Contributions Made to the Literature and the Container Terminal Industry

First, this study used a detailed discrete event simulation model to evaluate the policies developed to maintain the productivity of a cluster of six STS cranes under increasingly restrictive peak power limitations. This model accurately represents all the processes in a CT, and is able to closely resemble the impact of the policy in the real-world. Consequently, this study makes contributions to both the literature by evaluating a peak shaving strategy in a detailed simulation model and the industry by presenting outcomes that closely resemble their impact in the real-world.

Second, this study makes a pioneering contribution to the existing literature by introducing operational policies designed to maintain productivity under increasingly restrictive peak power limitations. It addresses a notable research gap by conducting a thorough investigation into the reduction of the productivity decline of the specific peak shaving strategy. Diverging from prior studies, this study encompasses a multi-objective of both reducing the peak power and preserving productivity. Leading to the second contribution made to the literature.

Third, based on the findings presented in Chapter 5, policies 2 and 3 are compared to policy 0 and policy 1 demonstrating their ability to maintain an unchanged level of productivity at balanced CT settings up to peak power limitations of 2800 kW and 2600 kW, respectively. These results are of particular significance to the CT industry, as they provide concrete evidence to support the adoption of these policies. This study makes a valuable second contribution to the industry by offering a practical tool that enables the reduction of the required reserved transport capacity by the grid operator for the CT while maintaining productivity, leading to significant cost savings regarding the contractual power demand related costs.

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# A. Research Paper

# Peak Shaving the Electrical Power Demand of Ship-to-Shore Cranes while Maintaining Productivity

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**Abstract.** The majority of ship-to-shore cranes have become electrically powered, leading to an increase in the required electrical power demand and to an increase in the volatility of the electrical power demand of container terminals. As a result, the contractual power demand charged by the grid operator, based on the maximum required power demand (peak power) at any moment in time, is upscaled. However, the highest required power demand values occur infrequently, leading to significant expenses for a resource that is rarely used. By implementing a peak shaving strategy, the peak power can be reduced, leading to a decrease in the contractual power demand related costs. Nevertheless, it is crucial to minimise the impact of the specific peak shaving strategy on the productivity of a container terminal to actually derive economic benefits from its implementation. The aim of this paper is to develop operational policies that effectively maintain productivity for a cluster of six ship-to-shore cranes under increasingly restrictive peak power limitations. A discrete event simulation approach was employed to evaluate the operational and economic impact of the developed policies. Based on the obtained results, implementing a peak power limitation using a 'priority-based' approach in conjunction with the use of adapted kinematic profiles can save a container terminal with six ship-to-shore cranes up to 107,545 euro per year, which is approximately 53% of the total contractual power demand related costs, without affecting the ship-to-shore cranes' productivity.

**Keywords:** Container Terminal · Electrification · Ship-to-Shore Cranes · Peak Power · Contractual Power Demand · Productivity.

## 1 Introduction

Climate change is one of the biggest challenges facing humanity, according to the European Environment Agency [1]. To mitigate climate change, greenhouse gas (GHG) emissions attributed to human activities must be reduced. Electrification of numerous end-users is a worldwide trend to address climate change, according to the International Energy Agency [3]. The trend to reduce GHG emissions by electrification, under pressure from international and regional institutions [12], has also reached container terminal (CT) operators. Consequently, more and more CT equipment is electrified, resulting in a reduction of local GHG emissions, in an increase in the required electrical power demand, and in an increase in the volatility of the electrical power demand.

To accommodate the increase in the required electrical power demand, grid operators must reserve additional transport capacity for the specific CT. As a result, the contractual power demand increases. The contractual power demand is based on the expected maximum required electrical power demand (peak power) at any moment in time. The Dutch grid operator Stedin charges 3.0473 euro per kW per month as a fee for the set contractual power demand. Ship-to-shore (STS) cranes and refrigerated containers are the primary contributors to the height of the contractual power demand determined for a CT, since both have a volatile and high electrical power demand. The volatile power demand of a cluster of six STS cranes is shown in Figure 1. The corresponding frequency distribution is presented in Figure 2.

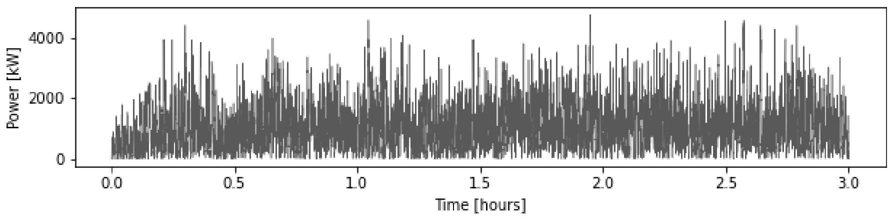



Fig. 1: Electrical power demand profile of a cluster of six Super Post Panamax STS cranes at ‘balanced’ CT settings

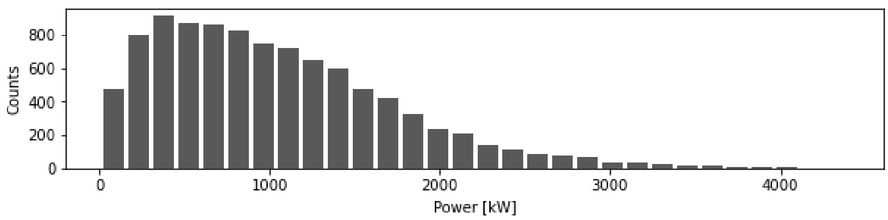



Fig. 2: Distribution of the power demand of a cluster of six Super Post Panamax STS cranes at ‘balanced’ CT settings

To illustrate, based on the power profile presented for a cluster of six STS cranes in Figure 1, the grid operator will set the contractual power demand to approximately 5000 kW. However, as outlined in Figure 2, the highest required power demand values occur infrequently. As a result, the CT operator incurs significant expenses for a resource that is rarely used.

By implementing a peak shaving strategy, the electrical peak power demand can be reduced and thereby the contractual power demand. This reduction leads to a direct decrease in the contractual power demand related costs, preferred by the CT operator, and indirectly to a more intensive use of the existing infrastructure, preferred by the grid operator. Nevertheless, it is crucial to minimise the impact of the specific peak shaving strategy on the productivity of a CT to actually derive economic benefits from its implementation.

**Research Objective and Question** The aim of this research is to investigate and identify operational policies that are able to maintain the productivity of a cluster of STS cranes while a peak power limitation is applied. Geerlings et al. [2] originally proposed the implementation of a peak power limitation as a peak shaving strategy for an entire CT terminal. Building upon the study conducted by Geerlings et al. [2], this research serves as an extension by specifically investigating methods to maintain productivity for a cluster of six STS cranes under increasingly restrictive peak power limitations. The policies developed are evaluated based on their operational and economic impact. The following research question is addressed:

> "*What is the operational and economic impact of the developed operational policies, aimed at maintaining productivity for a cluster of six STS cranes under increasingly restrictive peak power limitations?*"

The organisation of the paper is as follows. Section 2 provides an overview of peak shaving strategies studied in the literature. In Section 3 the developed peak shaving strategies are introduced, including the methodology applied to assess them. Section 4 presents the results obtained. Finally, Section 5 discusses and concludes the conducted study.

## 2 Peak Shaving Strategies for STS cranes: a Short Overview of the Literature

High peaks in electricity demand occur when electrically driven terminal equipment is operating simultaneously to handle container vessels as quickly as possible [2,6,7]. Peak shaving strategies applied by the CT's operator are required to suppress the contractual power demand related costs. Various peak shaving strategies are presented in the literature and can be categorised into three categories: (1) Power Sharing: store energy in a non-peak period and use it in a peak period, (2) Load Shifting: shift loads from a peak period to a non-peak period, and (3) Load Shedding: turn off loads during a peak period [4].

An overview of the peak shaving strategies for STS cranes studied in the literature is presented in Table 1. The applied measures can be classified into three groups: (1) operational constraint (OC), (2) regenerative energy (RE), and (3) energy storage system (ESS). The measure of using regenerated energy is either combined with an ESS (an ultracapacitor (UC) or a flywheel (FW)) or with an OC. In combination with an ESS, the ESS is charged during lowering and braking activities. In combination with an OC, lowering and hoisting movements are aligned, such that the regenerated energy from one crane can directly function as a power source for another crane.

The performance of the peak shaving strategies presented in the literature is most often expressed by the load factor or by the percentage change of the initial peak power. The load factor is defined as the average power divided by the peak power. The impact on the overall CT productivity, expressed as the number of boxes handled per time unit, is usually not included.

Table 1: Peak load reduction strategies for STS cranes

| ID | Method | Approach | RE | ESS (power kW) | OC | Result Peak power reduction | Reference |
|---|---|---|---|---|---|---|---|
| 1 | System design | UC in crane drive, charged by RE and grid (constant) | Yes | UC (1350) | No | -90% | [9] |
| 2 | System design | UC in crane drive, charged by RE | Yes | UC (905) | No | -60% | [10] |
| 3 | Optimisation | Fixed delay between DCs | No | No | Yes | -43% | [11] |
| 4 | | + ESS charged by RE | Yes | UC (1908), FW (3375) | Yes | -74% | |
| 5 | Particle Swarm Optimisation | Fixed delay between DCs (11s) | Yes | No | Yes | -82% | [6] |
| 6 | | Variable delay between DCs | Yes | No | Yes | -82% | |
| 7 | Discrete-event Simulation | Limiting simultaneously hoisting | No | No | Yes | -38% | [2] |
| 8 | | Limiting max. energy demand | No | No | Yes | -48% | |
| 9 | Agent-based Simulation | Limiting simultaneously hoisting. With double cycling mode. | No | No | Yes | -37% | [13] |
| 10 | | Limiting max. energy demand. With double cycling mode. | No | No | Yes | -58% | |
| 11 | Hierarchical control strategy | UC in crane drive charged by RE | Yes | UC (2048) | No | -49% | [5] |
| 12 | Particle Swarm Optimisation | DC coordination | Yes | No | Yes | -44% | |
| 13 | | + UC in crane drive charged by RE | Yes | UC (unknown) | Yes | -62% | |

# 3 Methodology

This research employs discrete event simulation (DES) to quantitatively assess the operational and economic impact of the developed policies. At first, the general methodology and the input parameters are outlined in Section 3.1. Subsequently, in Section 3.2, each policy is presented individually, along with an explanation of its operational rules and the specific methodologies used for its implementation.

## 3.1 Methodology in General

DES is utilised in this study to precisely model the operations of a CT and thoroughly evaluate the effectiveness of the developed policies. The employed DES model is based on the foundational simulation model developed by Portwise, ensuring a comprehensive and accurate representation. This sophisticated simulation model serves as a highly detailed depiction of a fictional CT, meticulously constructed to capture and depict the key operational aspects with precision. This involves defining the relevant entities such as containers, automated guided lift vehicles, STS cranes, and storage areas, along with their attributes and interrelationships. Additionally, the model incorporates the physical layout of the CT.

To address the research question effectively, specific modules have been purposefully designed and seamlessly integrated into the existing model. This section exclusively discusses the modules directly related to the research objective. The physical layout of the modelled CT is outlined comprehensively as first in this section. Subsequently, the methodology applied to model the power consumption is presented, followed by the methodology applied for implementing the peak power limitation. Lastly, the model is verified and subjected to a sensitivity analysis.

**Description of the Modelled Container Terminal** Figure 3 provides a cross-section of the physical layout of the simulated CT. Six dual-trolley STS cranes load and unload a container vessel. A group of automated guided lift vehicles (AGLV) transfers containers between the STS cranes and the stacking yard. The stacking yard consists of multiple stacks. Each stack has 34 bays, 10 rows, and 5 tiers. Two rubber mounted gantry (RMG) cranes operate in one stack. The RMG cranes are bound to one stack and cannot pass each other.

In this research, two CT settings are modelled, each representing a different situation regarding the limiting factor of the STS cranes. The scenarios are outlined in Table 2. The main difference between both CT settings is the influence of a denied movement, due to a lack of power, on the productivity. In the first scenario, CT operations are balanced, meaning that STS cranes, AGLV, and RMG cranes operate at levels that closely resemble realistic CT settings and neither of them can be appointed as the bottleneck regarding the overall CT productivity. In this setting, it is likely that a STS crane has to wait for an AGLV to arrive.

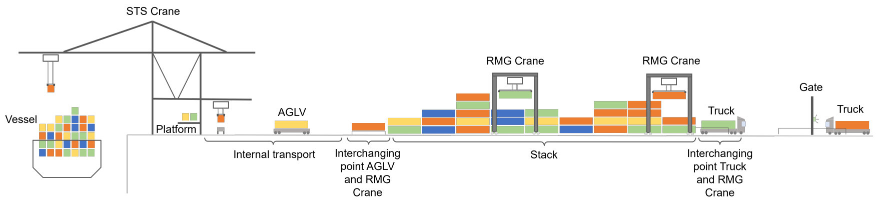



Fig. 3: Caption

Meaning that additional waiting times caused by a lack of power might not have a direct adverse impact on the productivity. In the second scenario, the impact of the AGLV and RMG cranes on the productivity of STS cranes is limited. In this setting, it is likely that the STS crane does not have to wait for an AGLV to arrive. Meaning that additional waiting times caused by a lack of power directly influence the productivity negatively.

Table 2: Terminal layout and equipment scenarios

| **Scenario** | **STS cranes** | **Productivity (LS)*** | **AGLVs** | **Productivity** | **RMG stacks** | **Productivity (WS)*** |
|---|---|---|---|---|---|---|
| Balanced | 6 | 58.8% | 25 | 45.7% | 12 | 78.4% |
| STS crane limiting | 6 | 65.5% | 35** | 52.3% | 31 | 31.4% |

*Percentile of total operating time in which specific equipment is productive for the landside (LS) or waterside (WS)
**Operating at unrealistic high velocity

Furthermore, containers are loaded on and discharged from the container vessel evenly in the model. 22.5% of the loaded containers are empty, 5% are reefers, and 72.5% are regular containers. 5% of the discharged containers are empty, 5% are reefers, and 90% are regular containers. Moreover, within this study only 40-ft containers are handled via a single-spreader. The weight distribution of the handled containers is presented in Table 3.

Table 3: Container weight distribution

| **Weight [ton]** | 0 | 15 | 10 | 15 | 20 | 25 | 30 | 35 | 40 |
|---|---|---|---|---|---|---|---|---|---|
| **Distribution** | 0 | 0 | 0.13 | 0.34 | 0.55 | 0.75 | 0.95 | 0.99 | 1 |

**Power Consumption** The trolleys are able to perform two types of movements: (1) trolley to waterside and (2) trolley to landside. Both trolley movements consume power. The spreader has four types of movements: (1) hoist to safety distance, (2) hoist from safety distance, (3) lower to safety distance, and (4) lower from safety distance. The 'hoisting' movements consume power. The 'lowering' movements generate energy. Important to note is that the regenerated energy is not utilised within this research.

The power profiles of the trolley and spreader (hoisting only) are depicted in Figure 4. These profiles are assumed to follow a linear pattern and can be divided into multiple line segments, each representing a specific phase of the movement. Line segments $l_1$ and $l_3$ correspond to the acceleration phase, while $l_2$ and $l_4$ represent the movement at a constant velocity. Lastly, segment $l_5$ represents the deceleration phase. The transition between these segments is indicated by the time values $t_0$, $t_1$, $t_2$, $t_3$, $t_4$, and $t_5$.

For the spreader movement, an additional acceleration state is presented. This is due to the imposed speed limitation during the initial part of the hoisting movement. Once the safety distance is reached at time instance $t_2$, the velocity is increased to the maximum allowed value.

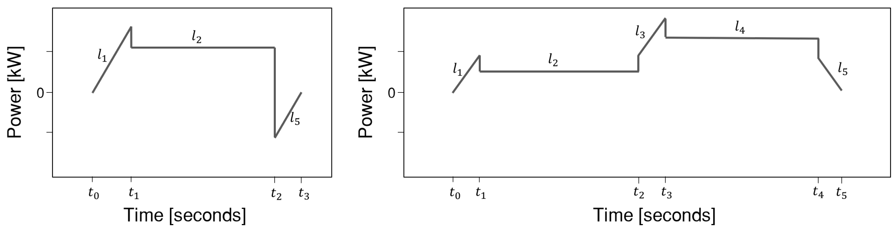



Fig. 4: Power profile of the trolley (left) and spreader (right)

The actual power and estimated power are recorded every tenth of a second for each movement. Additionally, to ensure that the peak power is captured, the values of $t_1$ and $t_3$ are rounded up. Once the boundaries of the line segments are established, the power at each tenth of a second can be calculated for each line segment using the formulas presented in Table 4. The speed fraction ($sf$) is calculated by dividing the velocity at the specific time interval by the maximum allowed velocity for a 40-ton container. Similarly, the weight factor ($wf$) is calculated by dividing the weight of the container by 40 tonne. The power values $P_{max}$, $P_{nom}$, and $P_{min}$ represent the maximum power used for a specific container weight (0 or 40 tonne), for the acceleration, constant velocity, and deceleration states, respectively.

Table 4: Formulas per line segment

| **Line segment** | **Formula** |
|---|---|
| $l_1$ | $P_{l1}(t) = \frac{(P_{max0t}+((P_{max40t}-P_{max0t})*wf))*sf}{t_1-t_0} * t$ |
| $l_2$ | $P_{l2}(t) = (P_{nom0t} + ((P_{nom40t} - P_{nom0t}) * wf)) * sf * t$ |
| $l_3$ | $P_{l3}(t) = \frac{(P_{max0t}+((P_{max40t}-P_{max0t})*wf))*sf}{t_1-t_0} * t + P_{l1}(t_1)$ |
| $l_4$ | $P_{l4}(t) = (P_{nom0t} + ((P_{nom40t} - P_{nom0t}) * wf)) * sf * t$ |
| $l_{5,trolley}$ | $P_{l5}(t) = \frac{(P_{min0t}+((P_{min40t}-P_{min0t})*wf*-1))*sf}{t_3-t_2} * t$ |
| $l_{5,spreader}$ | $P_{l5}(t) = \frac{(P_{min0t}+((P_{min40t}-P_{min0t})*wf*-1))*sf}{t_5-t_4} * t$ |

**Implementation of the Peak Power Limitation** A peak power limitation, suggested and studied by Geerlings et al. [2], is applied in this study as peak shaving strategy. In this strategy, the power of an upcoming movement is estimated. Thereafter, it is checked whether this power fits within the applied peak power limitation. If the movement fits, the specific equipment gets permission to start immediately. If not, the movement is postponed, after which it is checked again to see if power is available.

The corresponding 'power constraint' is presented in Equation 1. Where the estimated power ($EP$) at each time instance $i$ should remain lower than or equal to the applied peak power limitation ($PPL$) minus the reserved power ($RP$) by other equipment at that same time instance $i$. The set $I$ represents the time values of the specific movement in increments of one-tenth of a second ($[t_{now}, t_{now+0.1}, ..., t_{end-0.1}, t_{end}]$).

$$EP_i \leq PPL - RP_i \; \forall \; i \epsilon I \tag{1}$$

The peak power limitation can be implemented according to different approaches. Geerlings et al. [2] implemented a peak power limitation on an entire CT consisting of six STS cranes according to the 'first come first serve' approach. The 'who fits is served' and 'priority based' approaches are evaluated and compared in this study on their operational and economic impact under increasingly restrictive peak power limitations. The possible approaches identified are briefly described below.

*I. Who fits is served* When the estimated power fits within the available power, the movement gets permission to start immediately. If not, the start of the movement is postponed for a certain period of time. After this time period, it is again checked whether the estimated power fits within the available power. Within this time period, other equipment is allowed to make a request and to start a movement. This cycle repeats itself until the movement gets permission to start.

*II. First come first serve* When the estimated power fits within the available power, the movement gets permission to start immediately. If not, the start of the movement is postponed for a certain period of time. After this time period, it is again checked whether the estimated power fits within the available power. Within this time period, other equipment is not allowed to make a request to start a movement. This cycle repeats itself until the movement gets permission to start.

*III. Priority based* At first, the requested movement gets a priority number based on the status of the AGLVs and/or the platform. For example, if the AGLV is already at the interchanging point, then the trolley movement towards the interchanging point will get a high priority (low value). If either this priority number is lower than or equal to the listed priority numbers of waiting movements, and the estimated power fits within the available power, the movement gets permission to start immediately. If the priority number is higher than the listed priority numbers of other waiting movements or the estimated power fits not within the available power, then the priority number of the specific movement is listed. After a certain period of time the request is re-evaluated according to the same cycle. This cycle repeats itself until the movement gets approval to start.

**Validation** A validation is performed on the estimated power module to check whether the estimated power matches the actual power and to check if the peak power lies below the applied peak power limitation. For the validation of the estimated power module, the actual power and the estimated power between the two hundredths of a second and the four hundredths of a second are compared. Within this time period of ten minutes, six STS cranes operate under the restriction of a peak power limitation of 2200 kW.

The estimated power and the actual power are plotted in Figure 5. Both lines show the same pattern, indicating that the actual power demand is properly estimated. At all times, the estimated power is slightly higher than the actual power, this is in line with the setup of the model. Moreover, the applied peak power limitation of 2200 kW has not been exceeded.

**Sensitivity Analyses** In order to assess the impact of the simulation time on the measured peak power at balanced CT settings, a sensitivity analysis was conducted. The peak power values were measured for different simulation times, and the results are summarised in Table 5. Due to computational limitations, the number of replications for the experiments with increasing simulation times was reduced.

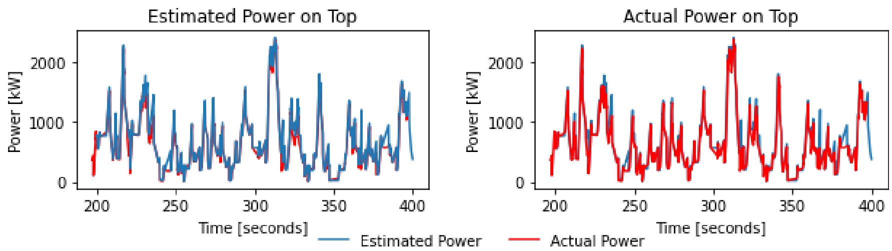



Fig. 5: Estimated power vs. Actual power

Table 5: Sensitivity analysis peak power at balanced CT settings

| Simulation time [hour] | Peak power per replication [kW] 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Max. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 4779 | 5131 | 4679 | 5541 | 4958 | 4746 | 4536 | 5466 | 4787 | 4979 | 4691 | 5541 |
| 6 | 5784 | 5357 | 5911 | 5060 | 5225 | 4358 | 5266 | | | | | 5911 |
| 9 | 5787 | 5240 | 5313 | 5399 | 4647 | | | | | | | 5787 |
| 12 | 5201 | 5193 | 4722 | 5597 | 5454 | | | | | | | 5597 |
| 15 | 5341 | 5543 | 6168 | 5138 | 5576 | | | | | | | 6168 |

Table 5 provides information on the relationship between simulation time and the maximum peak power measured. Comparing the results to the three-hour simulation time, it can be observed that the six-hour simulation time resulted in a 6.7% increase in the maximum measured peak power. The nine-hour simulation time showed a 4.4% increase, the twelve-hour simulation time showed a 1.0% increase, and the fifteen-hour simulation time showed a 11.3% increase.

It can be concluded that the simulation time does not consistently impact the measured maximum peak power, as the values observed fall within a range of approximately 5500 kW to 6200 kW. However, caution should be exercised when interpreting the peak power values obtained from a three-hour simulation run, as they may not represent the absolute maximum peak power that can be reached. Further analysis and experimentation with longer simulation times and more replications may be necessary to fully explore and understand the upper limits of the peak power in this context. This study does not specifically focus on obtaining the exact peak power for a CT with six operating STS cranes, and therefore, the deviation in the peak power can be justified.

### 3.2 Policy Specific Methodology

This section provides a detailed description of the policies developed. A brief overview of the policies developed is presented in Table 6.

Table 6: Overview all policies

| **Scope:** | | Cluster of 6 STS cranes | | |
|---|---|---|---|---|
| **Methodology:** | | Discrete event simulation | | |
| **ID** | **Peak Shaving Strategy** | **Approach** | **Kinematic Profile(s)** | **CT Setting** |
| Policy 0 | Peak power limitation | Who fits is served | 1 | STS crane limiting |
| Policy 0 | Peak power limitation | Who fits is served | 1 | Balanced |
| Policy 1 | Peak power limitation | Who fits is served | Multiple | STS crane limiting |
| Policy 1 | Peak power limitation | Who fits is served | Multiple | Balanced |
| Policy 2 | Peak power limitation | Priority based | 1 | Balanced |
| Policy 3 | Peak power limitation | Priority based | Multiple | Balanced |

**Policy 0** Policy 0 represents the least sophisticated policy in terms of intelligence. Its primary objective is to mitigate peak power consumption by imposing a peak power limitation based on the 'who fits is served' approach. This policy does not incorporate any supplementary measures aimed at maintaining productivity under increasingly restrictive peak power limitations. The methodology of policy 0 is visualised in Figure 6.

**Policy 1** Policy 1 aims to maintain productivity under increasingly restrictive power peak limitations by allowing the application of adapted kinematic profiles. The working principle of policy 1 is visualised in Figure 7. If the kinematic profile violates the power constraint, an optimisation-embedded simulation is employed

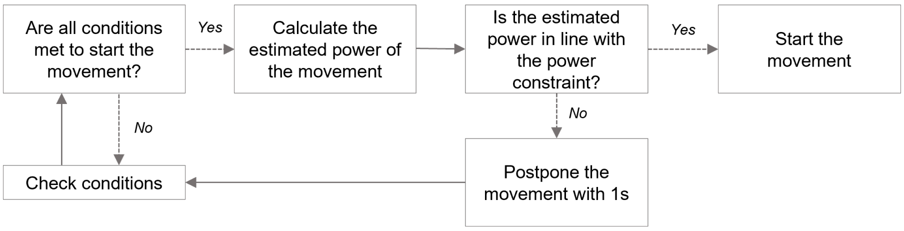



Fig. 6: Representation of Policy 0

to determine near-optimal solution sets using a metaheuristic combining Simulated Annealing with a Local Search heuristic (based on the study by Martin et al. [8]).

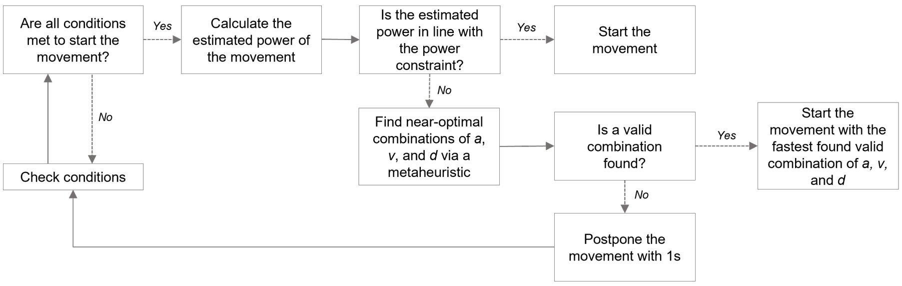



Fig. 7: Representation of Policy 1

The pseudocode of this metaheuristic is described in Figure 8. At first, several parameters are set. $P$ is the percentage accepted delay, $T_{initial}$ the initial temperature, $T_{stop}$ the stopping temperature, and $a_{max}$, $v_{max}$, and $d_{max}$ are the maximum values for the acceleration, velocity, and deceleration. Secondly, the initial solution set is set, consisting of the maximum values for acceleration, velocity, and deceleration. Subsequently, the action time for the initial solution set is calculated ($t_{initial}$). If this kinematic profile is in line with the stated constraint in Equation 1, the initial solution set becomes the executed solution set. The executed solution set contains the values for acceleration, velocity, and deceleration at which the movement is going to be executed. Conversely, if this kinematic profile is not in line with the stated constraint, a Local Search over the initial solution set is done. Six new solutions sets are created $\{a + 0.1,v,d\}$, $\{a - 0.1,v,d\}$, $\{a,v + 0.1,d\}$, $\{a,v - 0.1,d\}$, $\{a,v,d + 0.1\}$, and $\{a,v,d - 0.1\}$. In case the acceleration, velocity, or deceleration value is higher than the upper bound, the value is set to the corresponding upper bound. In case the acceleration, velocity, or deceleration value is smaller than 0.1, the value is set to 0.1. Thereafter, each created solution set is assessed on its validness.

Set $P,\ T_{inital},\ cooling\ rate,\ T_{stop},\ a_{\max},\ v_{\max},\ d_{\max}$
Set the initial solution set $\{a_{\max}\ ,\ v_{\max}\ ,\ d_{\max}\}$

Determine $t_{inital}$

If $EP_i \leq PC\ -\ RP_i\ \forall\ i \in I$ then
Executed solution set = initial solution set
End of Method.
Else
Compute a Local Search over the initial solution set by creating 6 new solution sets
Determine $t_{operational}$ for each new solution set

Loop for all new solution sets
If $t_{operational}\ \leq\ t_{inital}\ *\ (1+\frac{P}{100})$ AND $EP_i \leq PC\ -\ RP_i\ \forall\ i \in I$
Solution set = valid
Else
Solution set = not valid

Current solution set = of all the valid solution sets the one with the lowest $t_{operational}$

While $T > T_{stop}$
Choose one variable of the current solution set randomly
Change the value of this variable randomly within the ranges:
a: $[0.2, 0.3, \ldots, a_{upper\ bound}\ -\ 0.1]$
v: $[0.2, 0.3, \ldots, v_{upper\ bound}\ -\ 0.1]$
d: $[0.2, 0.3, \ldots, d_{upper\ bound}\ -\ 0.1]$
Check if all values in the solution set are within the above stated ranges
If not, change that value to the closest value within the specific range
Compute a Local Search over the current solution set by creating 6 new solution sets (same as above)
Determine $t_{operational}$ for each new solution set

Loop for all new solution sets
If $t_{operational}\ \leq\ t_{inital}\ *\ (1+\frac{P}{100})$ AND $EP_i \leq PC\ -\ RP_i\ \forall\ i \in I$
Solution set = valid
Else
Solution set = not valid

New solution set = of all the valid solution sets the one with the lowest $t_{operational}$

$delta\ =\ t_{operational,\ new\ solution\ set}\ -\ t_{operational,\ current\ solution\ set}$
If $delta\ <\ 0$ OR $z\_uniform(1{,}0{,}1)\ <\ e^{\frac{-delta}{T}}$
$Current\ solution\ set\ =\ New\ solution\ set$

$T\ =\ T\ -\ cooling\ rate$

Executed solution set = of all the appeared valid current solution sets the one with the lowest $t_{operational}$

End of Method.

Fig. 8: Pseudocode of the metaheuristic to find near-optimal solution sets

A solution set is valid if it is in line with both presented constraints. The first constraint implies that the operational time of the new found solution set ($t_{operational}$) must be less than $t_{initial}$ plus a certain accepted delay (time constraint). This accepted delay, parameter $P$, is set to a value of 20% in this study. The current solution set becomes, out of all valid created solution sets, the one with the lowest operational time ($t_{operational}$). If neither solution set is valid, the solution set with the lowest $t_{operational}$ is selected, furthermore its $t_{operational}$ value is increased by a thousand seconds. After a Local Search is conducted over the initial solution set a 'kick' is applied on the current solution set. The value of one randomly chosen variable in the current solution set is randomly changed to a value within the corresponding range. In case the acceleration, velocity, or deceleration value is higher than the upper bound, the value is set to the corresponding upper bound. In case the acceleration, velocity, or deceleration value is smaller than 0.1, the value is set to 0.1. A repetition of the code, explained above, is executed. With the Simulated Annealing metaheuristic it is decided whether the new solution set is accepted or not. As long as $T > T_{stop}$, a new 'kick' to the current solution set is executed. Conversely, if $T < T_{stop}$, an executed solution set is chosen. This executed solution set is a valid solution set that become a current solution set with the lowest value of $t_{operational}$.

An experiment has been conducted to assess the performance of the metaheuristic in finding near-optimal solution sets that adhere to the constraints. A comparison was made between the near-optimal solution set obtained by the metaheuristic and the optimal solution set, which was obtained by exhaustively checking all possible solution sets. On average, the near-optimal solution set generated by the metaheuristic for trolley movements ranked in the top 0.62% of all solution sets, with a standard deviation of 0.57%. Similarly, for spreader movements, the near-optimal solution set ranked in the top 0.18% of all solution sets, with a standard deviation of 0.15%.

Moreover, the computational time required by the metaheuristic was approximately less than half a second. On the other hand, the computational time needed to obtain the optimal solution set through exhaustive checking all possible solutions was significantly longer, taking approximately 2 to 5 seconds. Due to the high frequency of occurrence, this would have led to significant (undesired) higher simulation times per experiment. These findings demonstrate the effectiveness of the metaheuristic in generating near-optimal solution sets within the boundaries and within a reasonable amount of time.

**Policy 2** Policy 2 is developed to maintain productivity under increasingly restrictive peak power limitations through the application of the 'priority based' approach. The objective of this approach is to utilise the waiting time of equipment in front of the platform or for an AGLV as time to wait for power. The prioritisation mechanism ensures that power resources are allocated effectively and prevents unnecessary movement initiations when power availability is limited. The working principle of policy 2 is visualised in Figure 9.

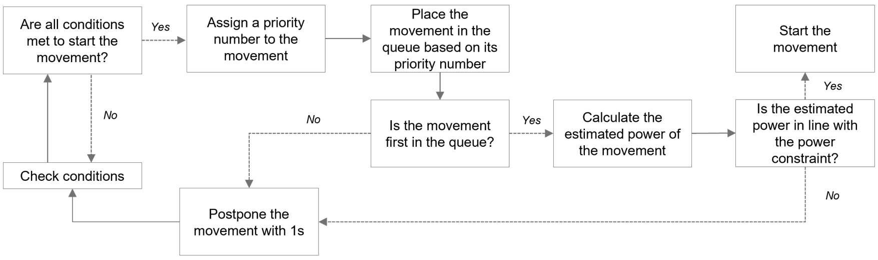



Fig. 9: Representation of Policy 2

This priority number is determined on the basis of the presence or status of the corresponding interacting equipment. For example, if a trolley intends to move from the platform to the interchange point with the AGLV, it is assigned a low priority number if the AGLV is already at the interchange point, and a high priority number if the AGLV is not present. After assigning a priority number to the movement, it is checked using Equation 2 if the priority number of the corresponding equipment, denoted as $PN_e$, is equal to or smaller than the priority numbers of all other equipment, denoted as $PN_k$, where $k$ represents the set of all equipment (except the corresponding equipment). If this is indeed the case, the estimated power demand is calculated and checked against the power constraint presented in Equation 1.

$$PN_e \leq PN_k \; \forall \; k \epsilon K \tag{2}$$

**Policy 3** Policy 3 is developed to maintain productivity under increasingly restrictive peak power limitations by combining policy 1 and policy 2. Herewith, the strengths of both policies are utilised. The working principle of policy 3 is visualised in Figure 10.

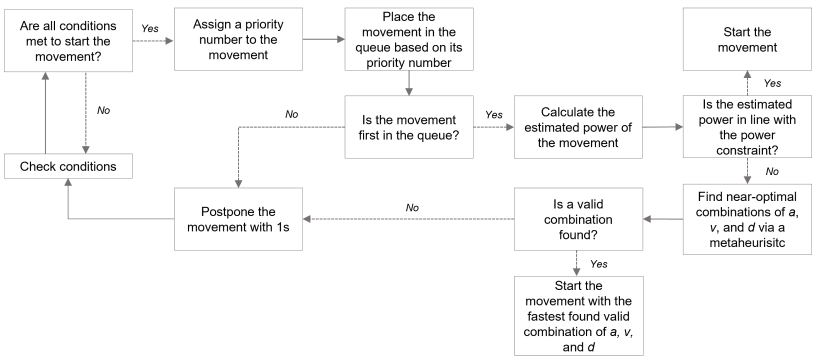



Fig. 10: Representation of Policy 3

## 4 Results

This section includes the operational and economic impact of the policies presented in Section 3.2. The operational impact is assessed through analysing the average productivity (handled boxes per hour) of the STS cranes, and the economic impact is assessed through analysing to what extent the yearly contractual power demand related costs can be reduced without impacting the productivity.

**Operational Impact** The decline in productivity for each policy under increasingly restrictive peak power limitations is presented in Figure 11a. Without any peak power limitation, the peak power demand for a cluster of six STS cranes was found to be 5,541 kW and 5,751 kW for balanced and STS crane limiting CT settings, respectively.

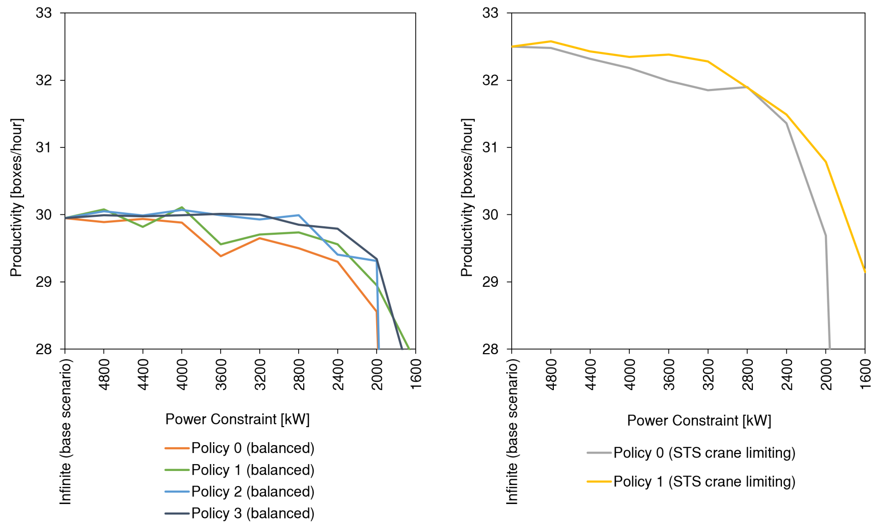
The percentile decrease in productivity is relatively smaller at balanced CT settings under increasingly restrictive peak power limitations compared to STS crane limiting CT settings for both policy 0 and policy 1. The discrepancy can be attributed to the specific configuration of the CT. In the STS crane limiting setting, the STS crane typically does not have to wait for an AGLV to arrive. Therefore, any delay in the initiation of a movement due to insufficient power availability directly impacts the STS crane's productivity.

A significant decline in the productivity is observed under policy 0 when the peak power limitation is set below 3800 kW for both settings. Additionally, the productivity massively declines when the peak power limitation is set below 2000 kW. This sharp drop can be attributed to the shutdown of certain STS cranes that are attempting to hoist the heaviest containers.

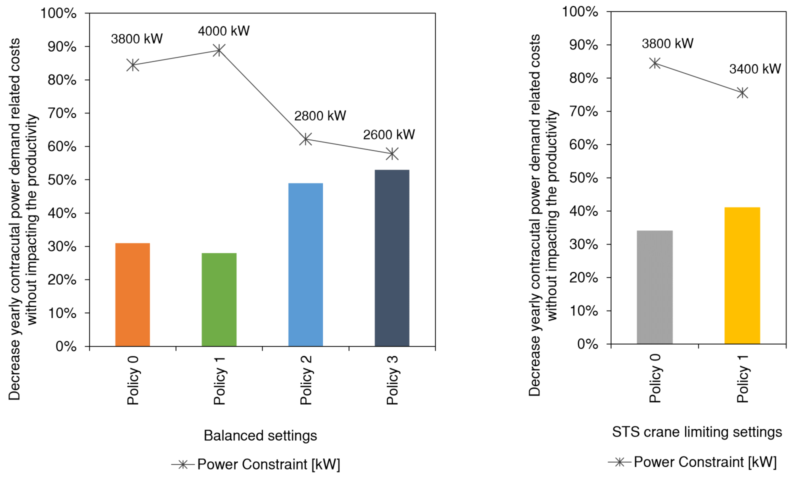
Policy 1 exhibits a similar pattern of productivity decline as policy 0 for both CT settings. However, there are notable differences between the two policies. Firstly, the productivity under policy 1, is in most peak power limitation scenarios slightly higher than the productivity under policy 0. Secondly, policy 1 experiences a less steep decline in the productivity for peak power limitations below 2000 kW. This can be attributed to the allowance of adapted kinematic profiles, which make it possible to handle the heaviest containers within the applied peak power limitation.

Policy 2 demonstrates a relatively stable and consistent productivity for peak power limitations up to 2800 kW. Eventually, the productivity for policy 2 exhibits a substantial decrease when the peak power limitation is set below 2000 kW, resembling the behaviour observed under policy 0.

Policy 3 demonstrates a relatively stable and consistent productivity for peak power limitations up to 2600 kW. A massive decline in the productivity is visible for peak power limitations of 2000 kW and below. Similar to policy 1, a less steep decline in the productivity for peak power limitations below 2000 kW is visible compared to policy 2. This can be attributed to the allowance of adapted kinematic profiles, which make it possible to handle the heaviest containers within the applied peak power limitation.




(a) Productivity decline under increasingly restrictive peak power limitations




(b) Maximum contractual power demand related cost savings without adversely impacting the productivity

Fig. 11: Operational and economic impact of the policies

Furthermore, in accordance with the objective of the ‘priority based’ approach policies, it was observed that the percentile time of trolley-spreader combinations waiting for an AGLV or in front of the platform was consistently lower for these policies compared to the ‘who fits is served’ approach policies. This observation suggest that the available power is effectively allocated to the most urgent movements that directly impact the productivity.

**Economic Impact** Without any peak power limitation the yearly contractual power demand related cost for a cluster of six STS cranes was found to be 202,621 euro and 210,300 euro for balanced and STS crane limiting CT settings, respectively. For every policy a critical peak power limitation is identified beyond which productivity is negatively impacted. At this critical peak power limitation, maximum contractual power demand related cost savings can be achieved while ensuring that productivity remains unharmed. Figure 11b presents the critical peak power limitations associated with each policy, along with the potential corresponding percentage reduction in the yearly contractual power demand related expenses.

## 5 Discussion and Conclusion

This section provides a comprehensive discussion and conclusion of the conducted study. The key findings addressing the research question are presented in Section 5.1. A detailed comparison between the findings of this study and the research conducted by Geerlings et al. [2] is presented in Section 5.2. The study’s limitations are discussed in Section 5.3. Furthermore, Section 5.4 provides recommendations for future research directions. Lastly, Section 5.5 highlights the contributions made by this study to the literature and the CT industry.

### 5.1 Key Findings

The implementation of a peak power limitation is an effective strategy to reduce the peak power demand consumption of a cluster of six STS cranes. With the implementation of a peak power limitation on a cluster of STS cranes, less transport capacity has to be reserved by the grid operator for the specific CT, resulting directly in a decrease in the contractual power demand related costs. Nonetheless, notable variations in effectiveness are observed among the evaluated policies. Furthermore, the effectiveness of the policies also varies across different CT settings. At first, the key findings regarding the operational impact of the policies are presented, followed by the economic impact. Lastly, a recommendation is presented based on the operational and economic impact of the evaluated policies.

**Operational Impact** First of all it can be concluded that the specific configuration of the CT, in terms of employed equipment, plays a crucial role regarding the impact of the applied peak power limitation on the STS cranes' productivity and therefore also the potential cost savings. The more limiting the STS cranes are in the overall CT productivity, the more aggressive the decline in the productivity under increasingly restrictive peak power limitations will be.

Secondly, the results indicate that the 'priority based' approach policies (policy 2 and policy 3) outperform the 'who fits is served' approach policies (policy 0 and policy 1) for peak power limitations above 2000 kW in terms of productivity preservation. It can be concluded that the 'priority based' approach effectively allocates the available power to the most urgent movements that directly impact the productivity.

Furthermore, for the 'who fits is served' approach policies, the allowance of adapted kinematic profiles improves the productivity for almost all peak power limitations at both CT settings. While, for the 'priority based' approach policies, the allowance of adapted kinematic profiles positively impacts the productivity solely for peak power limitations below 2800 kW. This can be attributed to the fact that the productivity decline under policy 2 starts below this peak power limitation.

**Economic Impact** Based on the obtained results, it can be concluded that the implementation of a peak power limitation of 2600 kW, following the 'priority based' approach, in conjunction with the adoption of adapted kinematic profiles (policy 3), leads to the most cost savings without adversely impacting the productivity. By applying a peak power limitation according to policy 3, 53% of the contractual power demand related costs can be reduced compared to the base scenario. However, without the adoption of adapted kinematic profiles (policy 2), a satisfactory reduction of 49% is achieved. The 'who fits is served' approach policies without (policy 0) and with the adoption of adapted kinematic profiles (policy 1) lead to a less decrease in the contractual power demand related cost of 31% and 28% at balanced CT settings and of 34% and 41% at STS crane limiting CT settings, respectively.

**Recommendation** It can be concluded, for balanced CT settings, that the developed 'priority based' approach, in comparison to the 'who fits is served' approach, is more effective in maintaining productivity under increasingly restrictive peak power limitations and therefore able to achieve the most cost savings. Additionally, when combined with adapted kinematic profiles, the 'priority based' approach (policy 3) exhibits the best performance in terms of operational and economic impact. By applying a peak power limitation of 2600 kW according to policy 3, the CT operator can obtain a reduction of 53% of the yearly contractual power demand related costs, which is the greatest recorded reduction of all created policies without affecting the productivity.

### 5.2 Comparison to Geerlings et al. [2]

The implementation of a peak power limitation as a peak shaving strategy was originally proposed by Geerlings et al. [2]. They applied a collective peak power limitation on an entire CT using the 'first come first serve' approach, with only the movements of STS cranes being postponed in case of power unavailability. Due to differences in study design, direct comparisons between the findings of this study and the work conducted by Geerlings et al. [2] are not feasible, however some meaningful comparisons can still be made.

The productivity decline for a cluster of six STS cranes under increasingly restrictive peak power limitations, as reported by Geerlings et al. [2], shows differences when compared to the results obtained in this study. The productivity reported by Geerlings et al. [2] is significantly higher. This discrepancy can be attributed to the simulation model differences, particularly to the absence of waiting time for AGLVs in Geerlings et al.'s [2] model. Furthermore, the decline in productivity starts at higher peak power limitations in this study compared to Geerlings et al.'s [2] findings. Additionally, the decline reported by Geerlings et al. [2] is less steep than the decline observed in this study under increasingly restrictive peak power limitations. This observation can be attributed to the differences in the weight distribution of containers, since in the study of Geerlings et al. [2] relatively lighter containers are handled, resulting in a lower overall power demand and a smaller decline in the reported productivity.

### 5.3 Limitations

This study offers insightful information on the possibility of peak shaving the power demand of a cluster of STS cranes while preserving productivity. However, it is important to acknowledge its limitations in order to maintain credibility and provide an accurate understanding of the conclusions drawn.

Firstly, it is important to acknowledge that this study was constrained by computational limitations, resulting in a restricted number of replications per experiment. Increasing the number of replications would have potentially enhanced the reliability and robustness of the study outcomes.

Secondly, the investigation was focused solely on a cluster of six dual trolley STS cranes. While these cranes are widely used in CTs, the findings may not be directly applicable to other types of cranes or different cluster sizes. Therefore, the generalizability of the results to a broader context should be interpreted with caution.

Furthermore, the contractual power demand related costs in this study are based on the fee charged by the Dutch gird operator Stedin. It should be noted that these charges can vary among different grid operators worldwide and change every year. Therefore, caution should be exercised when interpreting the cost savings associated with the reduction of the set contractual power demand, and a thorough re-evaluation is recommend for each specific situation.

Despite the acknowledged limitations, the results of this study remain valid in addressing the research question and contributing to the understanding of the operational and economic impact of the developed policies. By presenting these limitations, readers are informed about the need for caution when drawing conclusions based on the presented results in different contextual settings.

### 5.4 Recommendations for Future Research

Based on the study conduced, several recommendations for future research are identified:

I. *Analysis of a single trolley STS.* This study focuses on a dual trolley STS cranes performing single movements. However, investigating the productivity decline for a single trolley STS crane would be insightful, particularly regarding the performance of the 'priority based' approach in the absence of a platform.

II. *Validation with different cluster sizes* This study considers a cluster of six STS cranes. To validate the obtained results, it would be valuable to explore the impact of the developed policies on the productivity by adapting the cluster size.

III. *Split cluster of STS cranes each having a own peak power limitation* The current study applies a collective peak power limitation on a cluster of six STS cranes, potentially causing one crane to block the others. Investigating the scenario where the cluster is split into smaller groups, each with its own peak power limitation would be particularly interesting for large cluster sizes.

IV. *Productivity decline for double cycling* The current study focuses on the productivity decline, for different policies, for increasingly restrictive peak power limitations during either loading or unloading operations. Exploring the impact of the developed policies on the productivity when double cycling is employed would provide valuable insights.

V. *Multiple acceleration/velocity/deceleration values in one move* Policy 1 and policy 3 allow the application of adapted kinematic profiles, however, only one acceleration, velocity, and deceleration value is picked. Investigating whether the productivity decline under these policies can be mitigated by employing multiple values for acceleration, velocity, or deceleration would be an intriguing avenue for future research.

VI. *Adapt kinematic profile based on the AGLV arrival time* In this study no policies are developed in which the kinematic profile is adapted on the arrival time of the corresponding AGLV. Assessing whether adapting the kinematic profile in this manner can smooth the power demand and reduce the productivity decline under increasingly restrictive peak power limitations would be a valuable investigation.

VII. *Inclusion of additional equipment* This study focuses on controlling the power demand of STS cranes, while a CT comprises out of various electrified equipment. Investigating the impact of a collective peak power limitation, according to the approaches investigated in this study, that include other equipment would be an interesting expansion to this study.

### 5.5 Contributions Made to the Literature and the Container Terminal Industry

First, this study used a detailed DES model to evaluate the developed policies under increasingly restrictive peak power limitations. This model accurately represents all the processes in a CT and is able to closely resemble the impact of the policy in the real world. Consequently, this study makes contributions to both the literature by evaluating a peak shaving strategy in a detailed DES model and the industry by presenting outcomes that closely resemble their impact in the real world.

Second, this study makes a pioneering contribution to the existing literature by introducing operational policies designed to maintain productivity under increasingly restrictive peak power limitations. It addresses a notable research gap by conducting a thorough investigation into the productivity decline of the specific peak shaving strategy. Diverging from prior studies, this study encompasses a multi-objective of both reducing the peak power and preserving productivity. Leading to the second contribution made to the literature.

Third, based on the findings presented in Section 4, policies 2 and 3 are, compared to policy 0 and policy 1, demonstrating their ability to maintain an unchanged level of productivity at balanced CT settings up to peak power limitations of 2800 kW and 2600 kW, respectively. These results hold particular significance for the CT industry, as they provide concrete evidence to support the adoption of these policies. This study makes a valuable second contribution to the industry by offering a practical tool that enables the reduction of the required reserved transport capacity by the grid operator for the CT while maintaining productivity, leading to significant cost savings regarding the contractual power demand related costs.

### Abbreviations

AGLV: automated guided lift vehicle; CT: container terminal; DC: duty cycle; DES: discrete event simulation; ESS: energy storage system; FW: flywheel; GHG: greenhouse gas; LS: landside; OC: operational constraint; RE: regenerated energy; RMG: rubber mounted gantry; TEU: twenty-foot equivalent unit; UC: ultracapacitor; WS: waterside.

### Acknowledgements

This paper has been composed in fulfilment of the requirements for a master thesis in the field of Mechanical Engineering at Delft University of Technology. The comprehensive thesis can be accessed in the TU Delft repository, bearing an identical title.

### Funding

This research received no specific grant from any funding agency.

### Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. Additionally data regarding the obtained results is openly available in the TU Delft repository student theses.

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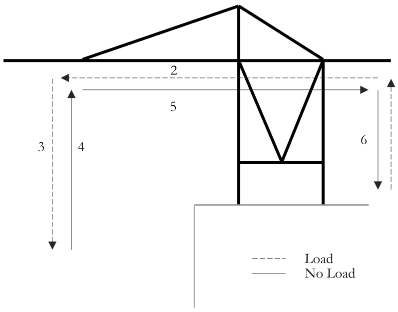
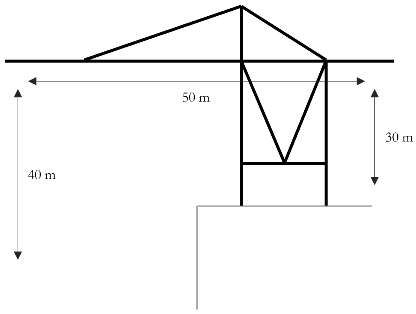
# B. Power Calculation

## B.1. Set Up




**((a))** Export cycle




**((b))** Dimensions of and average Post Panamax STS crane

**Figure B.1:** External input for power profile determination

## B.2. Characteristics

**Table B.1:** Kinematic behaviour, motor specs, loads, and dimensions of an average Super Post Panamax STS crane for the trolley movement

| | Symbol | Load | No Load | Unit |
|---|---|---|---|---|
| *Kinematic behaviour* | | | | |
| Friction coefficient | $\mu$ | 0.005 | 0.005 | - |
| Velocity | $v_{trolly}$ | 2.5 | 2.5 | $m/s$ |
| Acceleration | $a_{acceleration}$ | 0.64 | 0.64 | $m/s^2$ |
| Deceleration | $a_{deceleration}$ | -0.4 | -0.4 | $m/s^2$ |
| *Motor specs* | | | | |
| Rated speed | $RPM$ | 1750 | 1750 | $RPM$ |
| Mechanical efficiency | $\eta_{mechanical}$ | 0.9 | 0.9 | - |
| Inertia | $I$ | 23.87 | 23.87 | $ton$*$m^2$ |
| *Load and dimensions* | | | | |
| Trolley load | $m_{trolly}$ | 33.5 | 33.5 | $ton$ |
| Trolley travel distance | $s_{trolly}$ | 40 | 40 | $m$ |

**Table B.2:** Kinematic behaviour, motor specs, loads, and dimensions of an average STS crane for hoisting and lowering

| | Symbol | Load | No Load | Unit |
|---|---|---|---|---|
| *Kinematic behaviour* | | | | |
| Velocity hoisting | $v_{hoisting}$ | 2 | 3 | $m/s$ |
| Velocity lowering | $v_{lowering}$ | 2 | 3 | $m/s$ |
| Acceleration hoisting | $a_{acceleration_hoisting}$ | 0.8 | 0.8 | $m/s^2$ |
| Deceleration hoisting | $a_{deceleration_hoisting}$ | -0.8 | -0.8 | $m/s^2$ |
| Acceleration lowering | $a_{acceleration_lowering}$ | 0.8 | 0.8 | $m/s^2$ |
| Deceleration lowering | $a_{deceleration_lowering}$ | -0.8 | -0.8 | $m/s^2$ |
| *Motor specs* | | | | |
| Rated speed | $RPM$ | 850 | 850 | $RPM$ |
| Mechanical efficiency | $\eta_{mechanical}$ | 0.88 | 0.88 | - |
| Inertia | $I$ | 83.8 | 83.8 | $ton$*$m^2$ |
| *Load and dimensions* | | | | |
| Maximum lifted load | $m_{lifted_load}$ | 80 | 0 | $ton$ |
| Lifting system load | $m_{lifting_system}$ | 30 | 30 | $ton$ |
| Vessel-boom | $s_{vessel_boom}$ | 20 | 20 | $m$ |
| Vessel-quay | $s_{vessel_quay}$ | 12 | 12 | $m$ |

# B.3. Power Formulas

Three types of loads can be identified: (1) gravity-based load, (2) acceleration/deceleration-based load, and (3) motor inertia. The power calculations are divided into trolley and hoisting/lowering .

## Trolley

Table B.3 provides the power formulas associated with the trolley movement for each load. In Table B.4, the loads contributing to a specific state are listed. For example, during acceleration, the maximum power obtained is a summation of the loads $T_1$, $T_2$, and $T_4$.

**Table B.3:** List of equations for the trolley movement

| Name | ID | Formula |
|---|---|---|
| Trolley load | $T_1$ | $\frac{m_{tot}*9.81*\mu*v_{trolly}}{\eta_{mechanical}}$ |
| Acceleration load | $T_2$ | $\frac{m_{tot}*v_{trolly}*a_{acceleration}}{\eta_{mechanical}}$ |
| Deceleration load | $T_3$ | $m_{tot} * v_{trolly} * a_{deceleration} * \eta_{mechanical}$ |
| Acceleration inertia load | $T_4$ | $\frac{I*\left(2\pi\frac{RPM}{60}\right)^2*a_{acceleration}}{v_{trolly}}$ |
| Acceleration lowering load | $T_5$ | $\frac{I*\left(2\pi\frac{RPM}{60}\right)^2*a_{acceleration}}{v_{trolly}}$ |

**Table B.4:** Summation of power loads for a certain state

| State | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ |
|---|---|---|---|---|---|
| Acceleration | * | * | | * | |
| Constant velocity | * | | | | |
| Deceleration | * | | * | | * |

## Hoisting/lowering

Table B.5 provides the power formulas associated with the hoisting and lowering movement for each load. In Table B.6, the loads contributing to a specific state are listed. For example, during acceleration at hoisting, the maximum power obtained is a summation of the loads $N_1$, $N_3$, and $N_7$.

**Table B.5:** List of equations for hoisting/lowering

| Name | ID | Formula |
|---|---|---|
| Hoisting load | $N_1$ | $\frac{m_{tot}*9.81*v_{hoisting}}{\eta_{mechanical}}$ |
| Lowering Load | $N_2$ | $m_{tot} * 9.81 * -v_{lowering} * \eta_{mechanical}$ |
| Acceleration hoisting load | $N_3$ | $\frac{m_{tot}*a_{acceleration_hoisting}*v_{hoisting}}{\eta_{mechanical}}$ |
| Deceleration hoisting load | $N_4$ | $m_{tot} * a_{deceleration_hoisting} * v_{hoisting} * \eta_{mechanical}$ |
| Acceleration lowering load | $N_5$ | $\frac{m_{tot}*a_{acceleration_lowering}*-v_{lowering}}{\eta_{mechanical}}$ |
| Deceleration lowering load | $N_6$ | $-m_{tot} * a_{deceleration_lowering} * -v_{lowering} * \eta_{mechanical}$ |
| Acceleration hoisting inertia load | $N_7$ | $\frac{I*\left(2\pi \frac{RPM}{60}\right)^2*a_{acceleration_hoisting}}{v_{hoisting}}$ |
| Deceleration hoisting inertia load | $N_8$ | $\frac{I*\left(2\pi \frac{RPM}{60}\right)^2*a_{deceleration_hoisting}}{v_{hoisting}}$ |
| Acceleration lowering inertia load | $N_9$ | $\frac{I*\left(2\pi \frac{RPM}{60}\right)^2*a_{acceleration_lowering}}{v_{lowering}}$ |
| Deceleration lowering inertia load | $N_{10}$ | $\frac{I*\left(2\pi \frac{RPM}{60}\right)^2*a_{deceleration_lowering}}{v_{lowering}}$ |

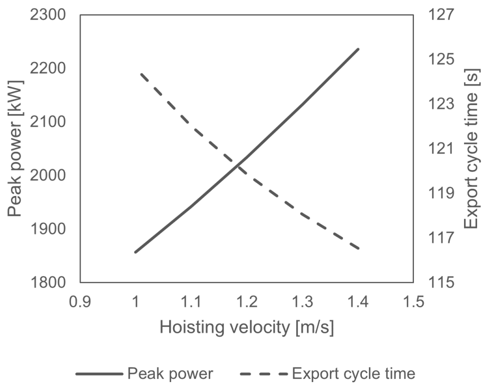
**Table B.6:** Summation of power loads for a certain state

| State | $N_1$ | $N_2$ | $N_3$ | $N_4$ | $N_5$ | $N_6$ | $N_7$ | $N_8$ | $N_9$ | $N_{10}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Hoisting acceleration | * | | * | | | | * | | | |
| Hoisting constant velocity | * | | | | | | | | | |
| Hoisting deceleration | * | | | * | | | | * | | |
| Lowering acceleration | | * | | | * | | | | * | |
| Lowering constant velocity | | * | | | | | | | | |
| Lowering deceleration | | * | | | | * | | | | * |

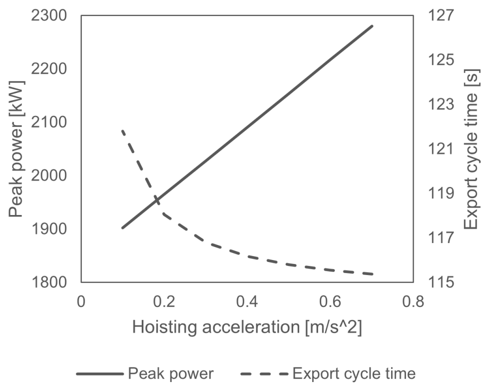
# C. Adapted Kinematics

Adaptations in the kinematic behaviour of a STS crane show a significant impact on the peak power as presented Table C.1. However, the cycle time is adversely affected. The relationship between the peak power and the cycle time are visualised in Figure C.1. From Figure C.1(a) it can be obtained that the hoisting velocity has a linear relationship with the peak power and export cycle time. From Figure C.1(b) it can be obtained that the acceleration rate has a linear relationship with the peak power and an exponential relationship with the export cycle time. It is therefore expected that the optimal combinations of 'hoisting velocity' and 'hoisting acceleration' do have a relative reduced acceleration rate and an almost unchanged velocity.

The best performing combinations are presented in Table C.1. These combinations were obtained systematically. At first, the peak load and export cycle time were noted for each combination of 'velocity hoisting' and 'acceleration hoisting'. Subsequently, combinations that outperformed other combinations were kept while the outperformed ones were eliminated. To illustrate, combination I has a peak load reduction of -20% an increase in the export cycle time of +3%. Combination II has a peak load reduction of -19% an increase in and export cycle time of +4%. Combination II is outperformed by combination I and is therefore eliminated while combination I is included till it gets outperformed by an other combination.




((a)) Hoisting velocity




((b)) Hoisting acceleration

**Figure C.1:** Relationship between hoisting velocity/acceleration, peak power, and and export cycle time

**Table C.1:** Percentile impact of adapting the kinematic behaviour during full load hoisting - the best combinations

| Velocity hoisting $[m/s]$ | Acceleration hoisting $[m/s^2]$ | Peak load $[kW]$ | Export cycle time $[s]$ |
|---|---|---|---|
| *Base scenario* | | | |
| 1.5 | 0.8 | 1954 | 115.239 |
| *Best performing combinations* | | | |
| 1.5 | 0.7 | -2.69% | +0.12% |
| 1.5 | 0.6 | -5.38% | +0.27% |
| 1.5 | 0.5 | -8.07% | +0.49% |
| 1.5 | 0.4 | -10.76% | +0.81% |
| 1.5 | 0.3 | -13.44% | +1.36% |
| 1.4 | 0.4 | -15.66% | +1.89% |
| 1.4 | 0.3 | -18.40% | +2.40% |
| 1.3 | 0.4 | -20.49% | +3.16% |
| 1.4 | 0.2 | -21.17% | +3.41% |
| 1.3 | 0.3 | -23.35% | +3.63% |

# D. Experiment - STS Crane Limiting Settings

The CT modelled in this study consists of six STS cranes. The STS cranes are equipped with two trolleys, with each trolley supporting a spreader. One trolley-spreader combination operates on the waterside, facilitating the transfer of containers between the platform and the container vessel. The other trolley-spreader combination functions operates on the landside, facilitating the transfer of containers between the platform and the AGLVs.

At STS crane limiting CT settings the impact of the AGLVs and RMG cranes must have a limited impact on the STS cranes' productivity. To achieve this one could increase the number of operating AGLVs. However, this increase the likelihood of AGLVs blocking each other. To avoid congestion among the operating AGLVs, the operating velocity of the AGLVs is set unrealistic high.

By means of an experiment the number of required AGLVs is determined for STS crane limiting CT settings. The status of a cluster of six STS cranes was investigated under different amounts of AGLVs employed in the CT. The average status of the STS cranes is presented in Figures D.1 and D.2 for the landside spreader-trolley combination and the waterside trolley-spreader combination, respectively. Up till approximately 35 employed AGLVs, the status at which the STS crane is productive increases. Consequently, 35 AGLVs are employed at STS crane limiting CT settings.

The stacking yard comprises 31 stacks, each equipped with two RMG cranes, one operating on the waterside and the other on the landside. The average waterside RMG crane remains idle for approximately 70% of the time operating in a CT with 35 AGLVs and six STS cranes. This finding suggests that the presence of a stacking yard with 31 stacks, each supported by two RMG cranes, does not have a negative effect on the productivity of the STSs cranes.

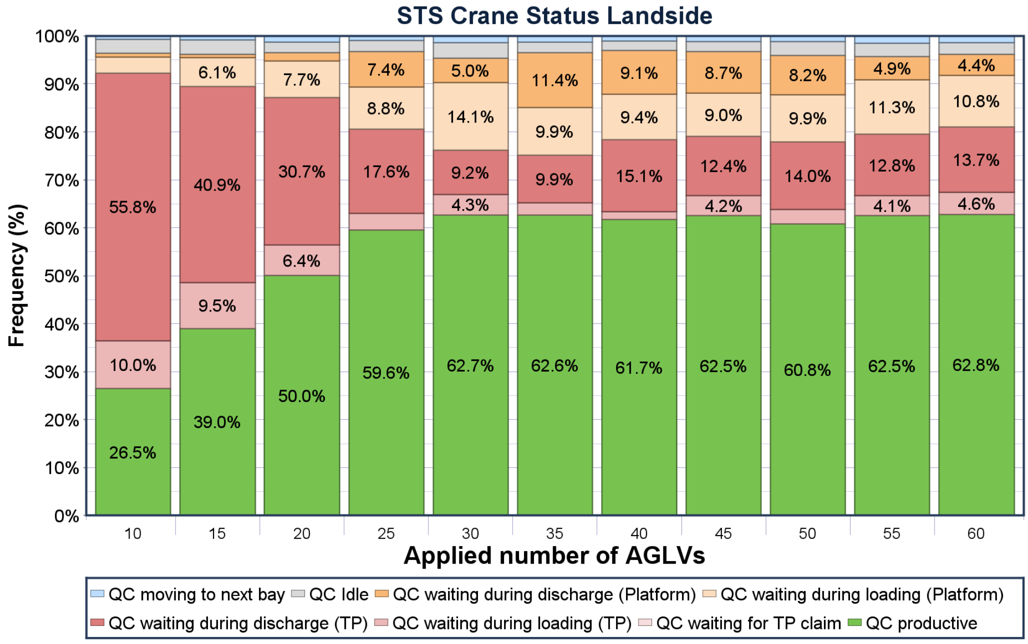



**Figure D.1:** STS crane status landside

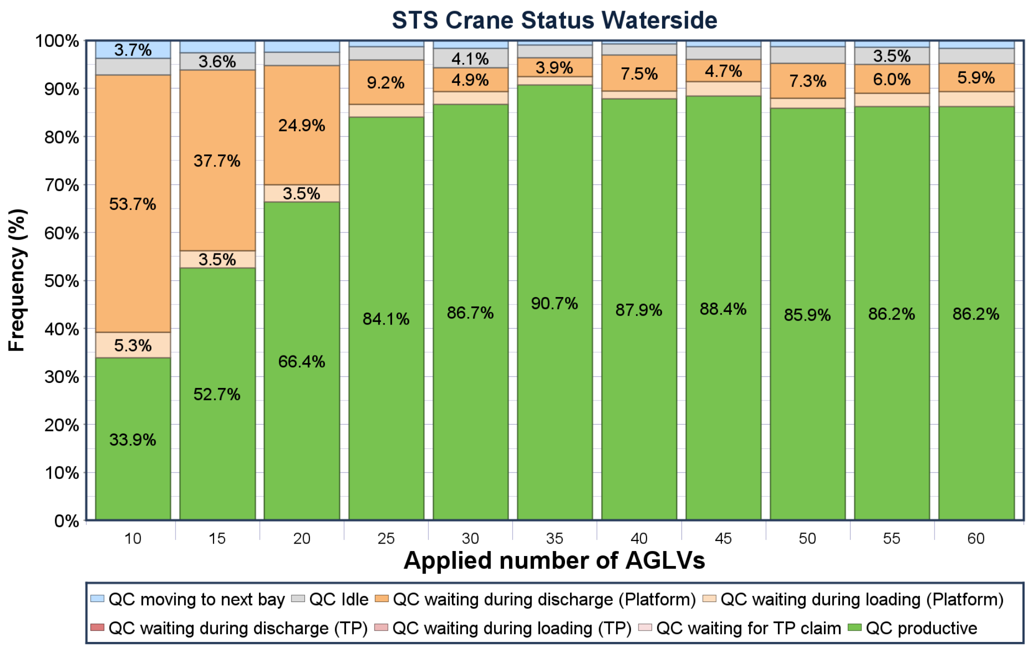



**Figure D.2:** STS crane status waterside

# E. Experiment - Parameter $P$

Policy 1 utilises a metaheuristic, which is subject to two constraints: E.1 and E.2. The first constraint requires that the estimated power ($EP$) at each time instance $i$ should remain lower than or equal to the applied peak power limitation ($PPL$) minus the reserved power ($RP$) by other equipment at that same time instance $i$. The set $I$ represents the time values of the movement in increments of one-tenth of a second, i.e., $[tnow, tnow + 0.1, ..., tend - 0.1, tend]$. The second constraint requires that the operational time of the solution set being investigated ($t_{operational}$) should not exceed the initial operational time ($t_{initial}$) (the initial operational time is the operational time obtained at the initial/conventional kinematic settings as outlined in Appendix B.2) plus a specific acceptable delay. The acceptable delay is determined by a percentage ($P$). For instance, if $t_{initial} = 10$ seconds and $P = 10$%, then the maximum acceptable $t_{operational}$ would be 11 seconds.

The percentage ($P$) is a user-defined parameter. An experiment was conducted to investigate the impact of the percentage ($P$) on the productivity while applying a peak power limitation of 2000 kW. The results of this experiment, presented in Figure E.1, indicate that the highest observed productivity occurred when a percentage accepted delay of 20% was employed. Consequently, in the experiments conducted for policy 1, parameter $P$ was set to 20%.

$$EP_i \leq PPL - RP_i \; \forall \; i \epsilon I \tag{E.1}$$

$$t_{operational} \leq t_{initial} * (1 + \frac{P}{100}) \tag{E.2}$$

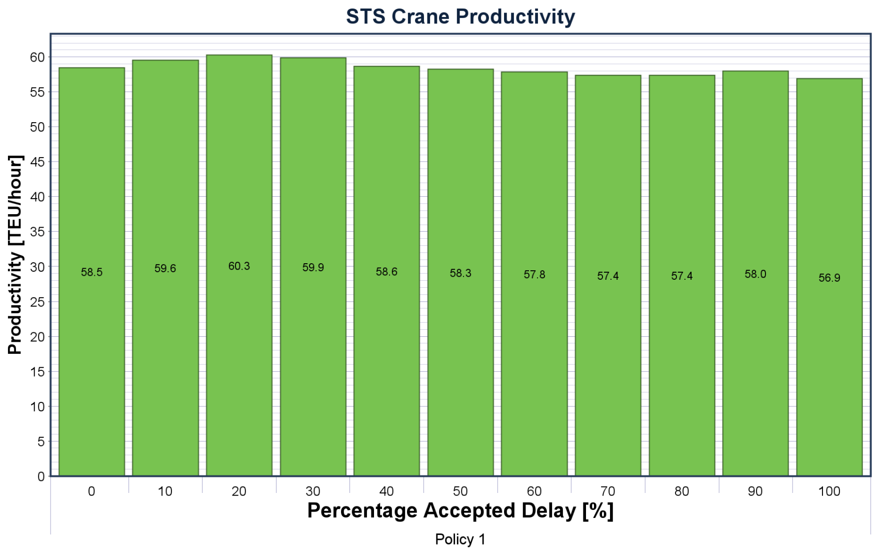



**Figure E.1:** Average productivity for multiple values of $P$, under an applied peak power limitation of 2000 kW

# F. Priority Numbers

In the following tables, the priority numbers for specific cases are presented. The platform capacity is represented by the values 0, 1, and 2, where 0 indicates no containers on the platform, 1 indicates one container on the platform, and 2 indicates two containers on the platform (full capacity). The status of the AGLV is denoted by 'yes' and 'no'. If the AGLV is at the interchanging point with the corresponding STS crane, the status is indicated as 'Yes', otherwise, it is indicated as 'no'.

## Unloading

**Table F.1:** Trolley priority numbers when unloading

| **Equipment:** | Trolley landside | | | Trolley landside | | | Trolley waterside | | |
|---|---|---|---|---|---|---|---|---|---|
| **Movement:** | Waterside | | | Landside | | | Waterside/Landside | | |
| | Platform | AGLV | PrioirtyNr | Platform | AGLV | PrioirtyNr | Platform | AGLV | PrioirtyNr |
| | 0 | no | 5 | 0 | no | 5 | 0 | no | 2 |
| | 1 | no | 4 | 1 | no | 4 | 1 | no | 3 |
| | 2 | no | 3 | 2 | no | 3 | 2 | no | 5 |
| | 0 | yes | 3 | 0 | yes | 2 | 0 | yes | 1 |
| | 1 | yes | 1 | 1 | yes | 1 | 1 | yes | 2 |
| | 2 | yes | 1 | 2 | yes | 1 | 2 | yes | 4 |

**Table F.2:** Spreader priority numbers when unloading

| **Equipment:** | Spreader landside | | | Spreader waterside | | |
|---|---|---|---|---|---|---|
| **Movement:** | Hoist platform/AGVL | | | Hoist platform/vessel | | |
| | Platform | AGLV | PrioirtyNr | Platform | AGLV | PrioirtyNr |
| | 0 | no | 5 | 0 | no | 2 |
| | 1 | no | 4 | 1 | no | 3 |
| | 2 | no | 3 | 2 | no | 5 |
| | 0 | yes | 2 | 0 | yes | 1 |
| | 1 | yes | 1 | 1 | yes | 2 |
| | 2 | yes | 1 | 2 | yes | 4 |

Loading

**Table F.3:** Trolley priority numbers when loading

| **Equipment:** | Trolley landside | | | Trolley landside | | |
|---|---|---|---|---|---|---|
| **Movement:** | Waterside | | | Landside | | |
| | Platform | AGLV | PrioirtyNr | Platform | AGLV | PrioirtyNr |
| | 0 | - | 1 | 0 | no | 3 |
| | 1 | - | 2 | 1 | no | 4 |
| | 2 | - | 5 | 2 | no | 5 |
| | | | | 0 | yes | 1 |
| | | | | 1 | yes | 1 |
| | | | | 2 | yes | 2 |

| **Equipment:** | Trolley waterside | | | Trolley waterside | | |
|---|---|---|---|---|---|---|
| **Movement:** | Waterside | | | Landside | | |
| | Platform | AGLV | PrioirtyNr | Platform | AGLV | PrioirtyNr |
| | 0 | - | 3 | 0 | - | 5 |
| | 1 | - | 1 | 1 | - | 2 |
| | | | | 2 | - | 1 |

**Table F.4:** Spreader priority numbers when loading

| **Equipment:** | Spreader landside | | | Spreader landside | | |
|---|---|---|---|---|---|---|
| **Movement:** | Hoist AGVL | | | Hoist Platform | | |
| | Platform | AGLV | PrioirtyNr | Platform | AGLV | PrioirtyNr |
| | 0 | - | 1 | 1 | no | 4 |
| | 1 | - | 2 | 2 | no | 5 |
| | 2 | - | 5 | 1 | yes | 1 |
| | | | | 2 | yes | 2 |

| **Equipment:** | Spreader waterside | | | Spreader waterside | | |
|---|---|---|---|---|---|---|
| **Movement:** | Hoist platfrom | | | Hoist vessel | | |
| | Platform | AGLV | PrioirtyNr | Platform | AGLV | PrioirtyNr |
| | 0 | - | 3 | 0 | - | 5 |
| | 1 | - | 1 | 1 | - | 2 |
| | | | | 2 | - | 1 |

# G. Additional Results

## G.1. Additional Figures

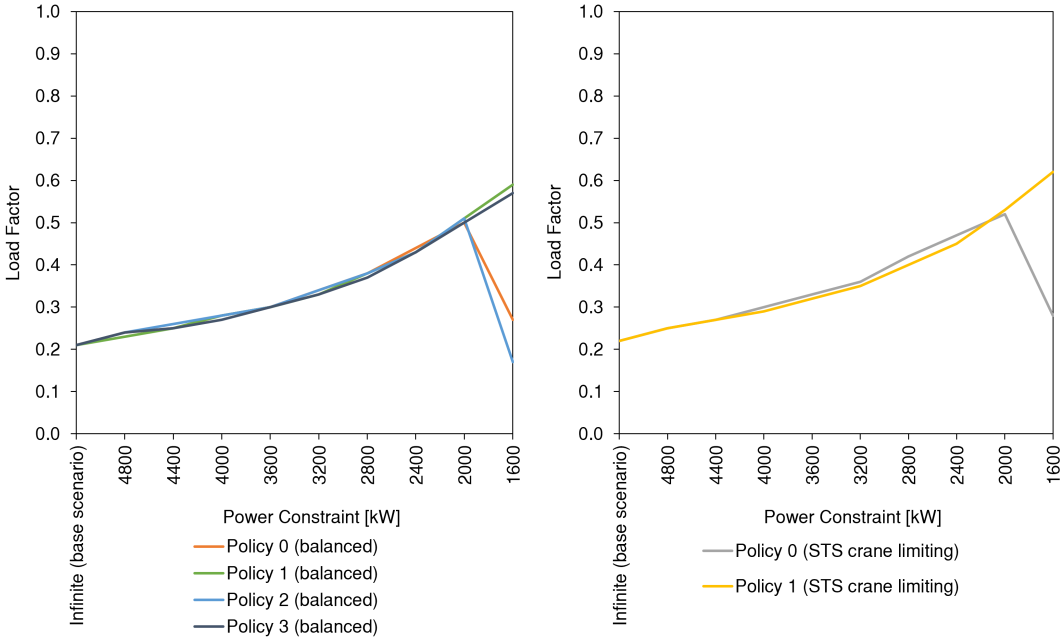



**Figure G.1:** Load factor

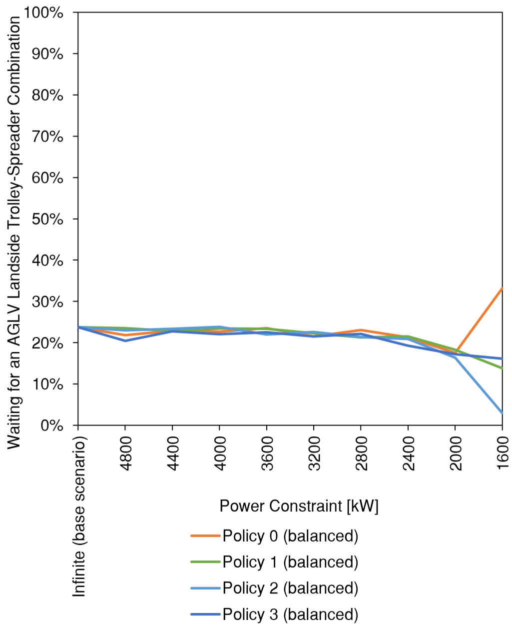



**Figure G.2:** Trade-off landside trolley-spreader combination waiting for AGLV and platform.

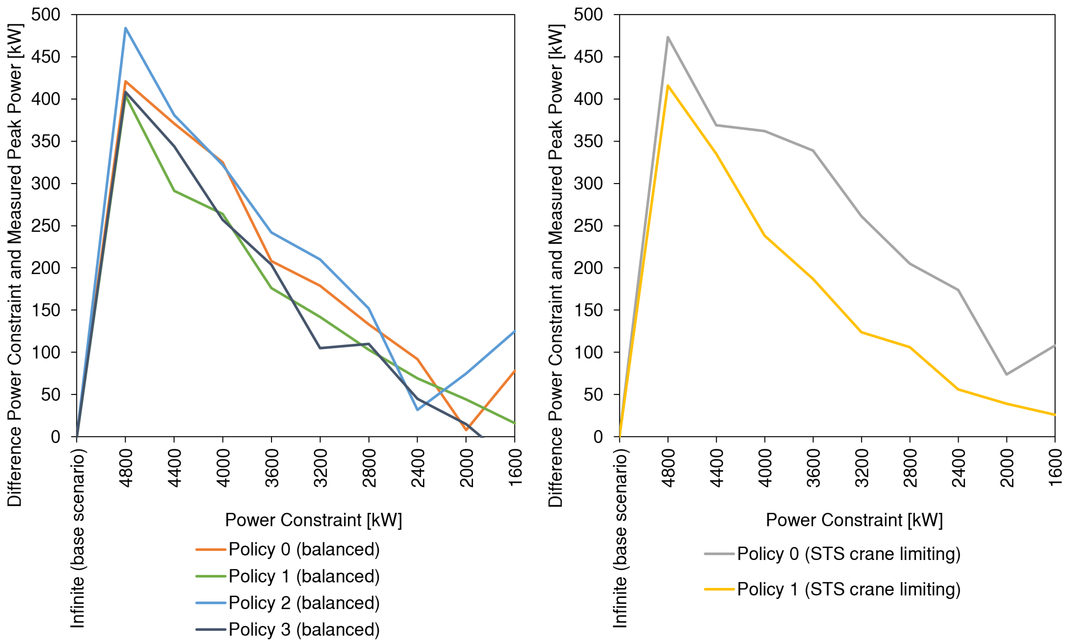



**Figure G.3:** Difference between the applied peak power limitation and measured peak power

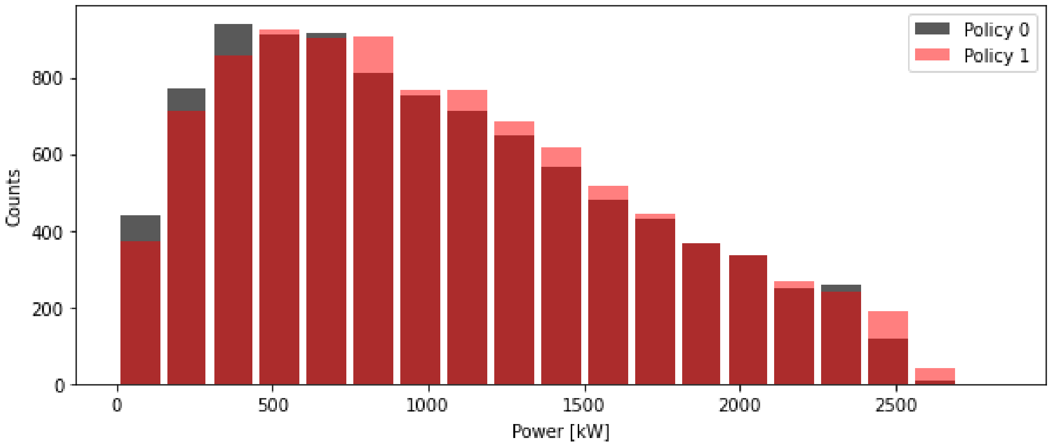



**Figure G.4:** Power distribution for policy 0 and policy 1 under a peak power limitation of 2800 kW

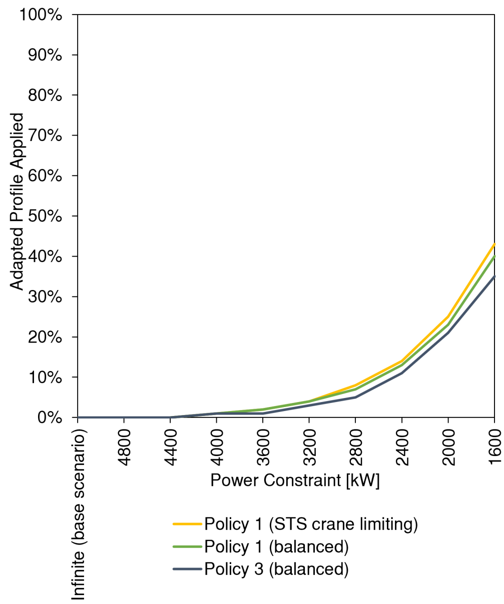



**Figure G.5:** Percentile of applied adapted kinematic profiles

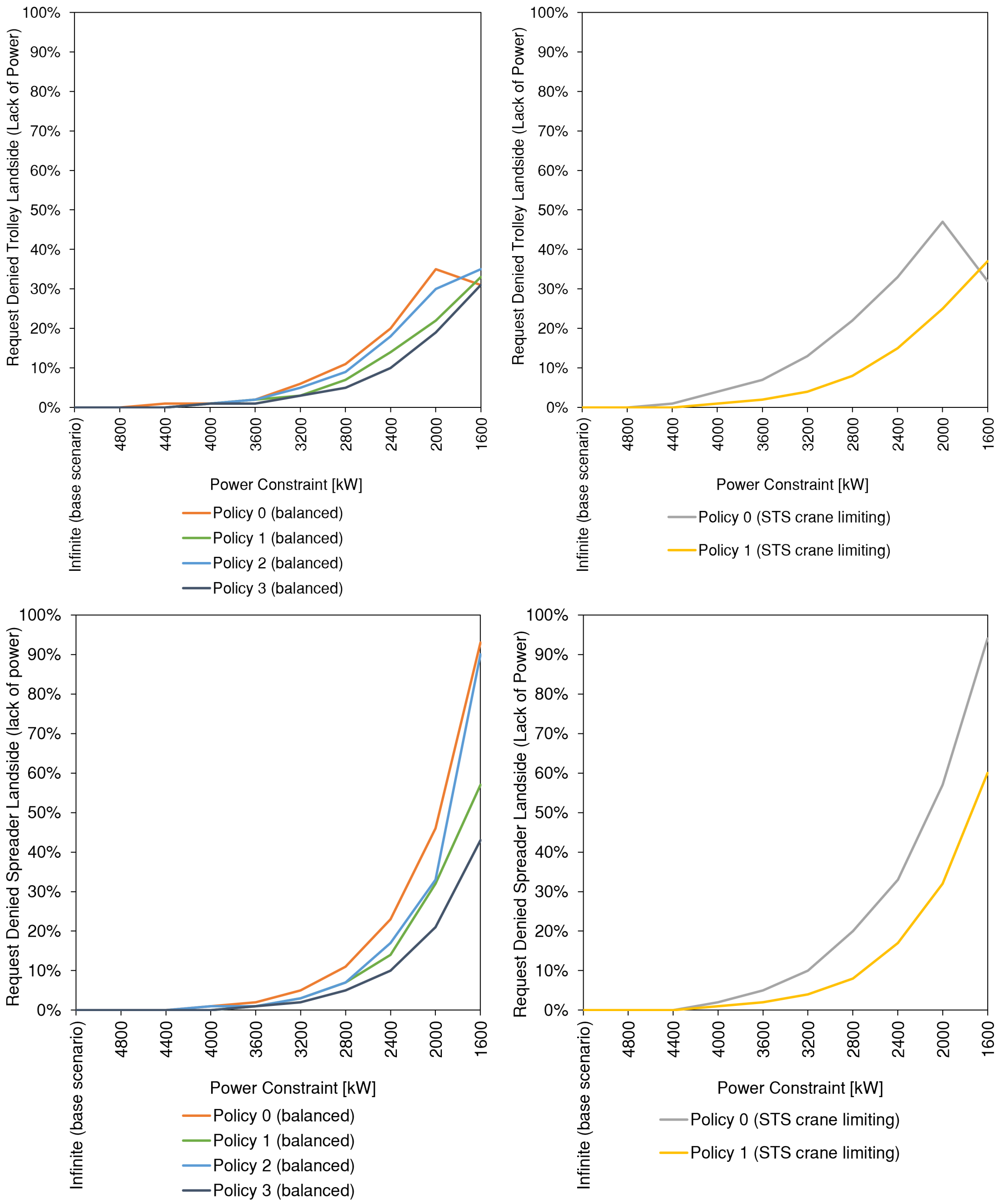



**Figure G.6:** Percentile of movements denied on the landside, due to insufficient power availability, for different peak power limitation scenario

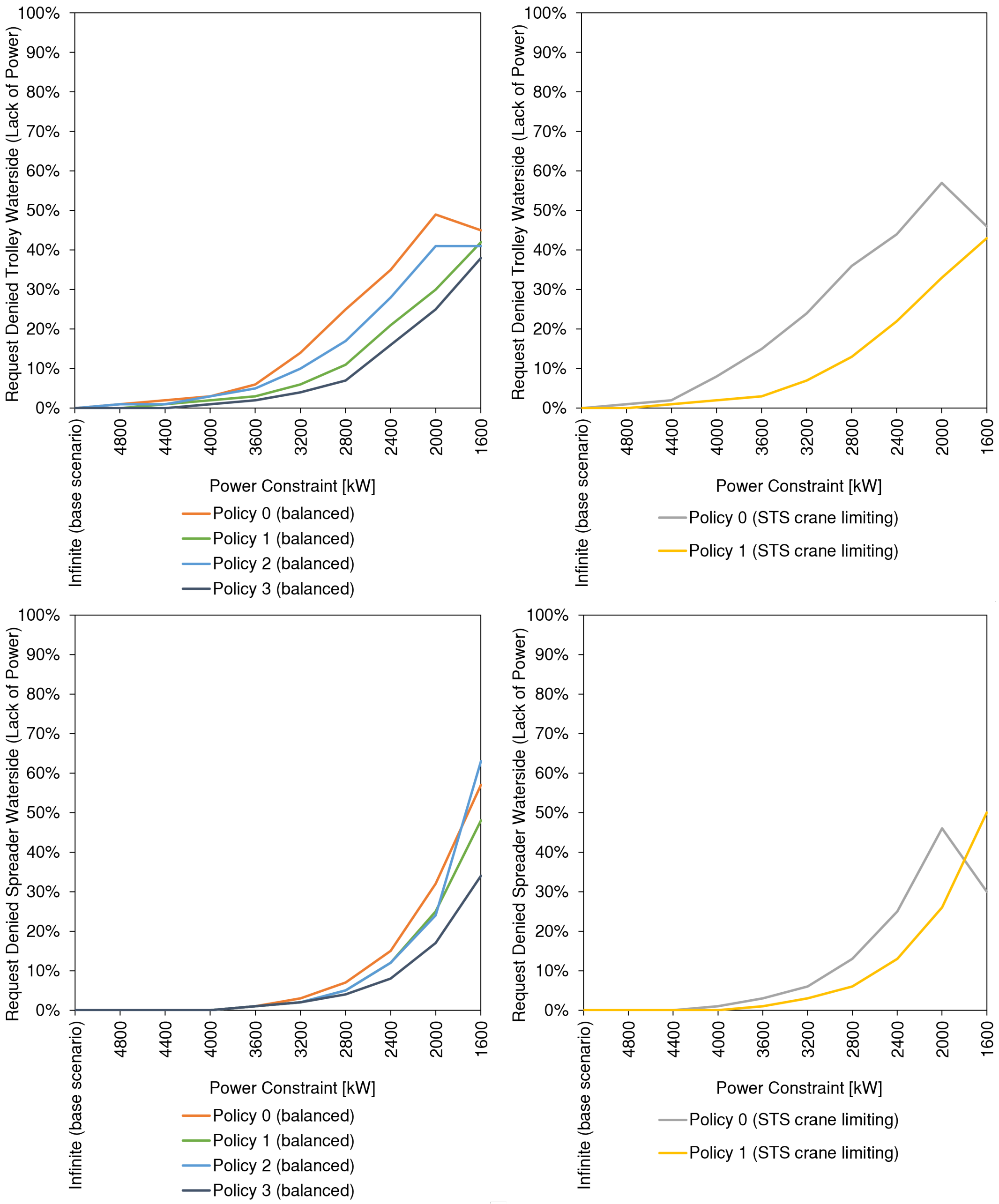



**Figure G.7:** Percentile of movements denied on the waterside, due to insufficient power availability, for different peak power limitation scenarios

## G.2. Data Overview

**Policy 0 (STS crane limiting)**

| Power constraint | Nr. of replications per experiment* | Measured average peak power | Delta | Yearly contractual power demand related costs | Reduction contractual power demand related costs | Productivity per STS crane | Reduction productivity per STS crane | Standard deviation productivity | Load factor | Outcome request for action Trolley Landside | | Outcome request for action Trolley Waterside | | Outcome request for action Spreader Landside | | Outcome request for action Spreader Waterside | | Total waiting time | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kW] | [-] | [kW] | [kW] | [€/year] | [-] | [box/hour] | [-] | [box/hour] | [-] | Approved | Denied | Approved | Denied | Approved | Denied | Approved | Denied | Landside | Waterside |
| Infinite (base scenario) | 13 | 5751 | 0 | 210300 | - | 32.5 | - | 1.006 | 0.22 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 31% | 5% |
| 4800 | 14 | 4327 | 473 | 175524 | -17% | 32.5 | 0% | 0.734 | 0.25 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 32% | 5% |
| 4600 | 14 | 4198 | 402 | 168211 | -20% | 32.4 | 0% | 0.857 | 0.26 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 33% | 4% |
| 4400 | 14 | 4031 | 369 | 160897 | -23% | 32.3 | -1% | 0.566 | 0.27 | 99% | 1% | 98% | 2% | 100% | 0% | 100% | 0% | 33% | 5% |
| 4200 | 12 | 3869 | 331 | 153584 | -27% | 32.7 | 1% | 0.767 | 0.28 | 99% | 1% | 97% | 3% | 100% | 0% | 100% | 0% | 32% | 6% |
| 4000 | 12 | 3638 | 362 | 146270 | -30% | 32.2 | -1% | 1.247 | 0.3 | 96% | 4% | 92% | 8% | 98% | 2% | 99% | 1% | 32% | 5% |
| 3800 | 13 | 3415 | 385 | 138957 | -34% | 32.4 | 0% | 0.699 | 0.31 | 95% | 5% | 90% | 10% | 97% | 3% | 98% | 2% | 33% | 8% |
| 3600 | 13 | 3261 | 339 | 131643 | -37% | 32.0 | -2% | 1.279 | 0.33 | 93% | 7% | 85% | 15% | 95% | 5% | 97% | 3% | 33% | 7% |
| 3400 | 12 | 3175 | 225 | 124330 | -41% | 31.9 | -2% | 1.040 | 0.34 | 90% | 10% | 81% | 19% | 93% | 7% | 95% | 5% | 32% | 5% |
| 3200 | 12 | 2939 | 261 | 117016 | -44% | 31.9 | -2% | 1.009 | 0.36 | 87% | 13% | 76% | 24% | 90% | 10% | 94% | 6% | 33% | 7% |
| 3000 | 13 | 2752 | 248 | 109703 | -48% | 31.6 | -3% | 1.114 | 0.38 | 84% | 16% | 73% | 27% | 87% | 13% | 92% | 8% | 31% | 5% |
| 2800 | 12 | 2595 | 205 | 102389 | -51% | 31.9 | -2% | 0.923 | 0.42 | 78% | 22% | 64% | 36% | 80% | 20% | 87% | 13% | 30% | 5% |
| 2600 | 11 | 2412 | 188 | 95076 | -55% | 31.6 | -3% | 1.204 | 0.44 | 72% | 28% | 61% | 39% | 74% | 26% | 80% | 20% | 31% | 6% |
| 2400 | 13 | 2226 | 174 | 87762 | -58% | 31.4 | -4% | 0.753 | 0.47 | 67% | 33% | 56% | 44% | 67% | 33% | 75% | 25% | 31% | 6% |
| 2200 | 12 | 2074 | 126 | 80449 | -62% | 30.3 | -7% | 1.157 | 0.49 | 60% | 40% | 49% | 51% | 55% | 45% | 67% | 33% | 29% | 6% |
| 2000 | 12 | 1926 | 74 | 73135 | -65% | 29.7 | -9% | 0.864 | 0.52 | 53% | 47% | 43% | 57% | 43% | 57% | 54% | 46% | 27% | 5% |
| 1800 | 14 | 1678 | 122 | 65822 | -69% | 17.8 | -45% | 8.195 | 0.35 | 66% | 34% | 55% | 45% | 10% | 90% | 65% | 35% | 26% | 19% |
| 1600 | 14 | 1492 | 108 | 58508 | -72% | 13.0 | -60% | 5.466 | 0.28 | 68% | 32% | 54% | 46% | 6% | 94% | 70% | 30% | 27% | 16% |

*Replications in which the productivity deviated significantly from the average productivity in an experiment, were eliminated to reduce the influence of outliers. Outliers were eleminated until a standard deviation of approximately 1 was achieved.

**Policy 0 (balanced)**

| Power constraint | Nr. of replications per experiment* | Measured average peak power | Delta | Yearly contractual power demand related costs | Reduction contractual power demand related costs | Productivity per STS Crane | Reduction productivity per STS crane | Standard deviation productivity | Load factor | Outcome request for action Trolley Landside | | Outcome request for action Trolley Waterside | | Outcome request for action Spreader Landside | | Outcome request for action Spreader Waterside | | Total waiting time | | Waiting time landside | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kW] | [-] | [kW] | [kW] | [€/year] | [-] | [box/hour] | [-] | [box/hour] | [-] | Approved | Denied | Approved | Denied | Approved | Denied | Approved | Denied | Landside | Waterside | AGV | Platform |
| Infinite (base scenario) | 11 | 5541 | 0 | 202621 | - | 30.0 | - | 1.002 | 0.21 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 39% | 12% | 24% | 76% |
| 4800 | 11 | 4379 | 421 | 175524 | -13% | 29.9 | 0% | 1.004 | 0.24 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 37% | 11% | 22% | 78% |
| 4600 | 13 | 4162 | 438 | 168211 | -17% | 30.0 | 0% | 0.999 | 0.25 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 38% | 12% | 22% | 78% |
| 4400 | 13 | 4029 | 371 | 160897 | -21% | 29.9 | 0% | 0.880 | 0.25 | 99% | 1% | 98% | 2% | 100% | 0% | 100% | 0% | 38% | 13% | 23% | 77% |
| 4200 | 14 | 3885 | 315 | 153584 | -24% | 30.1 | 0% | 1.078 | 0.27 | 99% | 1% | 98% | 2% | 99% | 1% | 100% | 0% | 38% | 12% | 23% | 77% |
| 4000 | 11 | 3675 | 325 | 146270 | -28% | 29.9 | 0% | 1.213 | 0.28 | 99% | 1% | 97% | 3% | 99% | 1% | 100% | 0% | 38% | 12% | 23% | 77% |
| 3800 | 12 | 3506 | 294 | 138957 | -31% | 30.1 | 0% | 1.156 | 0.30 | 98% | 2% | 95% | 5% | 99% | 1% | 99% | 1% | 37% | 10% | 21% | 79% |
| 3600 | 8 | 3392 | 208 | 131643 | -35% | 29.4 | -2% | 0.849 | 0.30 | 98% | 2% | 94% | 6% | 98% | 2% | 99% | 1% | 39% | 12% | 24% | 76% |
| 3400 | 12 | 3186 | 214 | 124330 | -39% | 29.5 | -2% | 0.808 | 0.32 | 96% | 4% | 90% | 10% | 97% | 3% | 98% | 2% | 38% | 11% | 23% | 77% |
| 3200 | 10 | 3021 | 179 | 117016 | -42% | 29.7 | -1% | 1.087 | 0.34 | 94% | 6% | 86% | 14% | 95% | 5% | 97% | 3% | 38% | 11% | 22% | 78% |
| 3000 | 11 | 2828 | 172 | 109703 | -46% | 29.5 | -2% | 1.130 | 0.36 | 93% | 7% | 84% | 16% | 94% | 6% | 96% | 4% | 38% | 12% | 23% | 77% |
| 2800 | 10 | 2667 | 133 | 102389 | -49% | 29.5 | -2% | 1.060 | 0.38 | 89% | 11% | 75% | 25% | 89% | 11% | 93% | 7% | 37% | 12% | 23% | 77% |
| 2600 | 14 | 2466 | 134 | 95076 | -53% | 29.4 | -2% | 1.137 | 0.41 | 86% | 14% | 72% | 28% | 85% | 15% | 90% | 10% | 38% | 12% | 23% | 77% |
| 2400 | 9 | 2308 | 92 | 87762 | -57% | 29.3 | -2% | 1.192 | 0.44 | 80% | 20% | 65% | 35% | 77% | 23% | 85% | 15% | 36% | 11% | 21% | 79% |
| 2200 | 9 | 2140 | 60 | 80449 | -60% | 28.9 | -4% | 1.054 | 0.46 | 74% | 26% | 61% | 39% | 69% | 31% | 78% | 22% | 37% | 11% | 21% | 79% |
| 2000 | 12 | 1992 | 8 | 73135 | -64% | 28.6 | -5% | 1.185 | 0.50 | 65% | 35% | 51% | 49% | 54% | 46% | 68% | 32% | 33% | 10% | 17% | 83% |
| 1800 | 11 | 1771 | 29 | 65822 | -68% | 27.3 | -9% | 1.027 | 0.54 | 58% | 42% | 46% | 54% | 40% | 60% | 56% | 44% | 33% | 10% | 17% | 83% |
| 1600 | 14 | 1522 | 78 | 58508 | -71% | 12.1 | -60% | 6.780 | 0.27 | 69% | 31% | 55% | 45% | 7% | 93% | 43% | 57% | 39% | 54% | 33% | 67% |

*Replications in which the productivity deviated significantly from the average productivity in an experiment, were eliminated to reduce the influence of outliers. Outliers were eleminated until a standard deviation of approximately 1 was achieved.

**Policy 1 (STS crane limiting)**

| Power constraint | Nr. of replications per experiment* | Measured average peak power | Delta | Yearly contractual power demand related costs | Reduction contractual power demand related costs | Productivity per STS Crane | Reduction productivity per STS crane | Standard deviation productivity | Load factor | Outcome request for action Trolley Landside | | Outcome request for action Trolley Waterside | | Outcome request for action Spreader Landside | | Outcome request for action Spreader Waterside | | Applied Profile | | Total waiting time | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kW] | [-] | [kW] | [kW] | [€/year] | [-] | [box/hour] | [-] | [box/hour] | [-] | Approved | Denied | Approved | Denied | Approved | Denied | Approved | Denied | initial | adapted | Landside | Waterside |
| Infinite (base scenario) | 13 | 5751 | 0 | 210300 | - | 32.5 | - | 1.006 | 0.22 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 32% | 5% |
| 4800 | 14 | 4384 | 416 | 175524 | -17% | 32.6 | 0% | 1.195 | 0.25 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 33% | 6% |
| 4600 | 14 | 4272 | 328 | 168211 | -20% | 32.6 | 0% | 0.861 | 0.25 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 32% | 6% |
| 4400 | 14 | 4065 | 335 | 160897 | -23% | 32.4 | 0% | 1.029 | 0.27 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 100% | 0% | 33% | 6% |
| 4200 | 14 | 3902 | 298 | 153584 | -27% | 32.6 | 0% | 0.741 | 0.28 | 99% | 1% | 99% | 1% | 100% | 0% | 100% | 0% | 99% | 1% | 33% | 5% |
| 4000 | 11 | 3762 | 238 | 146270 | -30% | 32.3 | -1% | 0.957 | 0.29 | 99% | 1% | 98% | 2% | 99% | 1% | 100% | 0% | 99% | 1% | 33% | 6% |
| 3800 | 12 | 3592 | 208 | 138957 | -34% | 32.5 | 0% | 0.953 | 0.30 | 99% | 1% | 97% | 3% | 99% | 1% | 99% | 1% | 99% | 1% | 32% | 5% |
| 3600 | 12 | 3413 | 187 | 131643 | -37% | 32.4 | 0% | 0.945 | 0.32 | 98% | 2% | 97% | 3% | 98% | 2% | 99% | 1% | 98% | 2% | 33% | 6% |
| 3400 | 13 | 3239 | 161 | 124330 | -41% | 32.4 | 0% | 1.181 | 0.34 | 97% | 3% | 95% | 5% | 98% | 2% | 98% | 2% | 97% | 3% | 32% | 6% |
| 3200 | 14 | 3076 | 124 | 117016 | -44% | 32.3 | -1% | 1.189 | 0.35 | 96% | 4% | 93% | 7% | 96% | 4% | 97% | 3% | 96% | 4% | 32% | 6% |
| 3000 | 14 | 2880 | 120 | 109703 | -48% | 32.1 | -1% | 0.933 | 0.37 | 95% | 5% | 91% | 9% | 95% | 5% | 96% | 4% | 95% | 5% | 32% | 5% |
| 2800 | 12 | 2694 | 106 | 102389 | -51% | 31.9 | -2% | 1.093 | 0.40 | 92% | 8% | 87% | 13% | 92% | 8% | 94% | 6% | 92% | 8% | 32% | 4% |
| 2600 | 11 | 2522 | 78 | 95076 | -55% | 32.2 | -1% | 1.196 | 0.43 | 89% | 11% | 83% | 17% | 88% | 12% | 91% | 9% | 89% | 11% | 32% | 5% |
| 2400 | 14 | 2344 | 56 | 87762 | -58% | 31.5 | -3% | 0.913 | 0.45 | 85% | 15% | 78% | 22% | 83% | 17% | 87% | 13% | 86% | 14% | 31% | 5% |
| 2200 | 14 | 2142 | 58 | 80449 | -62% | 31.1 | -4% | 0.899 | 0.49 | 81% | 19% | 74% | 26% | 77% | 23% | 81% | 19% | 81% | 19% | 32% | 4% |
| 2000 | 14 | 1961 | 39 | 73135 | -65% | 30.8 | -5% | 1.029 | 0.53 | 75% | 25% | 67% | 33% | 68% | 32% | 74% | 26% | 75% | 25% | 31% | 4% |
| 1800 | 14 | 1772 | 28 | 65822 | -69% | 29.9 | -8% | 1.025 | 0.57 | 69% | 31% | 61% | 39% | 55% | 45% | 65% | 35% | 67% | 33% | 30% | 3% |
| 1600 | 14 | 1574 | 26 | 58508 | -72% | 29.1 | -10% | 0.941 | 0.62 | 63% | 37% | 57% | 43% | 40% | 60% | 50% | 50% | 57% | 43% | 27% | 3% |

*Replications in which the productivity deviated significantly from the average productivity in an experiment, were eliminated to reduce the influence of outliers. Outliers were eleminated until a standard deviation of approximately 1 was achieved.

**Policy 1 (balanced)**

| Power constraint | Nr. of replications per experiment* | Measured average peak power | Delta | Yearly contractual power demand related costs | Reduction contractual power demand related costs | Productivity per STS Crane | Reduction productivity per STS crane | Standard deviation productivity | Load factor | Outcome request for action Trolley Landside | | Outcome request for action Trolley Waterside | | Outcome request for action Spreader Landside | | Outcome request for action Spreader Waterside | | Applied profile | | Total waiting time | | Waiting time landside | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kW] | [-] | [kW] | [kW] | [€/year] | [-] | [box/hour] | [-] | [box/hour] | [-] | Approved | Denied | Approved | Denied | Approved | Denied | Approved | Denied | Initial | Adapted | Landside | Waterside | AGV | Platform |
| Infinite (base scenario) | 11 | 5541 | 0 | 202621 | - | 30.0 | - | 1.200 | 0.21 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 39% | 12% | 24% | 76% |
| 4800 | 14 | 4396 | 404 | 175524 | -13% | 30.1 | 0% | 0.798 | 0.23 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 38% | 12% | 24% | 76% |
| 4600 | 14 | 4239 | 361 | 168211 | -17% | 29.9 | 0% | 1.004 | 0.24 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 39% | 12% | 23% | 77% |
| 4400 | 12 | 4109 | 291 | 160897 | -21% | 29.8 | -1% | 1.249 | 0.25 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 100% | 0% | 38% | 13% | 23% | 77% |
| 4200 | 14 | 3920 | 280 | 153584 | -24% | 29.9 | 0% | 0.848 | 0.27 | 99% | 1% | 99% | 1% | 100% | 0% | 100% | 0% | 99% | 1% | 39% | 12% | 23% | 77% |
| 4000 | 12 | 3736 | 264 | 146270 | -28% | 30.1 | 0% | 0.922 | 0.28 | 99% | 1% | 98% | 2% | 100% | 0% | 100% | 0% | 99% | 1% | 38% | 12% | 23% | 77% |
| 3800 | 12 | 3578 | 222 | 138957 | -31% | 29.8 | -1% | 1.166 | 0.29 | 99% | 1% | 97% | 3% | 99% | 1% | 99% | 1% | 99% | 1% | 37% | 11% | 23% | 77% |
| 3600 | 13 | 3424 | 176 | 131643 | -35% | 29.6 | -1% | 1.179 | 0.3 | 98% | 2% | 97% | 3% | 99% | 1% | 99% | 1% | 98% | 2% | 39% | 12% | 23% | 77% |
| 3400 | 10 | 3215 | 185 | 124330 | -39% | 29.7 | -1% | 1.221 | 0.32 | 98% | 2% | 96% | 4% | 98% | 2% | 99% | 1% | 98% | 2% | 38% | 11% | 21% | 79% |
| 3200 | 14 | 3058 | 142 | 117016 | -42% | 29.7 | -1% | 1.143 | 0.33 | 97% | 3% | 94% | 6% | 97% | 3% | 98% | 2% | 96% | 4% | 38% | 12% | 22% | 78% |
| 3000 | 12 | 2879 | 121 | 109703 | -46% | 29.7 | -1% | 1.140 | 0.35 | 95% | 5% | 92% | 8% | 95% | 5% | 97% | 3% | 95% | 5% | 38% | 10% | 21% | 79% |
| 2800 | 13 | 2697 | 103 | 102389 | -49% | 29.7 | -1% | 0.558 | 0.38 | 93% | 7% | 89% | 11% | 93% | 7% | 95% | 5% | 93% | 7% | 38% | 11% | 21% | 79% |
| 2600 | 12 | 2517 | 83 | 95076 | -53% | 29.7 | -1% | 0.938 | 0.4 | 91% | 9% | 85% | 15% | 90% | 10% | 92% | 8% | 91% | 9% | 37% | 10% | 21% | 79% |
| 2400 | 12 | 2331 | 69 | 87762 | -57% | 29.6 | -1% | 1.213 | 0.43 | 86% | 14% | 79% | 21% | 86% | 14% | 88% | 12% | 87% | 13% | 36% | 11% | 22% | 78% |
| 2200 | 11 | 2135 | 65 | 80449 | -60% | 29.6 | -1% | 1.002 | 0.47 | 82% | 18% | 74% | 26% | 78% | 22% | 82% | 18% | 82% | 18% | 36% | 10% | 18% | 82% |
| 2000 | 12 | 1956 | 44 | 73135 | -64% | 29.0 | -3% | 0.868 | 0.51 | 78% | 22% | 70% | 30% | 68% | 32% | 75% | 25% | 77% | 23% | 37% | 9% | 18% | 82% |
| 1800 | 14 | 1769 | 31 | 65822 | -68% | 28.9 | -4% | 1.131 | 0.55 | 70% | 30% | 63% | 37% | 58% | 42% | 65% | 35% | 68% | 32% | 34% | 8% | 15% | 85% |
| 1600 | 14 | 1584 | 16 | 58508 | -71% | 27.8 | -7% | 0.878 | 0.59 | 67% | 33% | 58% | 42% | 43% | 57% | 52% | 48% | 60% | 40% | 32% | 7% | 14% | 86% |

*Replications in which the productivity deviated significantly from the average productivity in an experiment, were eliminated to reduce the influence of outliers. Outliers were eleminated until a standard deviation of approximately 1 was achieved.

**Policy 2 (balanced)**

| Power constraint | Nr. of replications per experiment* | Measured average peak power | Delta | Yearly contractual power demand related costs | Reduction contractual power demand related costs | Productivity per STS Crane | Reduction productivity per STS crane | Standard deviation productivity | Load factor | Outcome request for action Trolley Landside | | Outcome request for action Trolley Waterside | | Outcome request for action Spreader Landside | | Outcome request for action Spreader Waterside | | Total waiting time | | Waiting time landside | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kW] | [-] | [kW] | [kW] | [€/year] | [-] | [box/hour] | [-] | [box/hour] | [-] | Approved | Denied | Approved | Denied | Approved | Denied | Approved | Denied | Landside | Waterside | AGLV | Platform |
| Infinite (base scenario) | 11 | 5541 | 0 | 202621 | - | 30.0 | - | 1.002 | 0.21 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 39% | 12% | | |
| | | | | | | | | | | | | | | | | | | | | 24% | 76% |
| 4800 | 13 | 4316 | 484 | 175524 | -13% | 30.0 | 0% | 1.150 | 0.24 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 38% | 11% | 23% | 77% |
| 4600 | 14 | 4212 | 388 | 168211 | -17% | 30.1 | 0% | 0.847 | 0.25 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 38% | 10% | 21% | 79% |
| 4400 | 13 | 4019 | 381 | 160897 | -21% | 30.0 | 0% | 1.060 | 0.26 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 38% | 13% | 23% | 77% |
| 4200 | 14 | 3843 | 357 | 153584 | -24% | 30.1 | 0% | 0.827 | 0.27 | 99% | 1% | 98% | 2% | 100% | 0% | 100% | 0% | 38% | 12% | 23% | 77% |
| 4000 | 14 | 3678 | 322 | 146270 | -28% | 30.1 | 0% | 1.048 | 0.28 | 99% | 1% | 97% | 3% | 99% | 1% | 100% | 0% | 38% | 12% | 24% | 76% |
| 3800 | 11 | 3492 | 308 | 138957 | -31% | 30.1 | 0% | 1.243 | 0.29 | 98% | 2% | 97% | 3% | 99% | 1% | 99% | 1% | 38% | 11% | 22% | 78% |
| 3600 | 14 | 3358 | 242 | 131643 | -35% | 30.0 | 0% | 0.932 | 0.30 | 98% | 2% | 95% | 5% | 99% | 1% | 99% | 1% | 38% | 11% | 22% | 78% |
| 3400 | 14 | 3174 | 226 | 124330 | -39% | 30.1 | 0% | 1.057 | 0.33 | 97% | 3% | 92% | 8% | 98% | 2% | 99% | 1% | 38% | 11% | 22% | 78% |
| 3200 | 14 | 2990 | 210 | 117016 | -42% | 29.9 | 0% | 0.913 | 0.34 | 95% | 5% | 90% | 10% | 97% | 3% | 98% | 2% | 37% | 12% | 23% | 77% |
| 3000 | 12 | 2834 | 166 | 109703 | -46% | 29.9 | 0% | 0.868 | 0.36 | 93% | 7% | 86% | 14% | 95% | 5% | 97% | 3% | 37% | 11% | 22% | 78% |
| 2800 | 12 | 2648 | 152 | 102389 | -49% | 30.0 | 0% | 1.009 | 0.38 | 91% | 9% | 83% | 17% | 93% | 7% | 95% | 5% | 37% | 10% | 21% | 79% |
| 2600 | 13 | 2481 | 119 | 95076 | -53% | 29.4 | -2% | 0.724 | 0.41 | 87% | 13% | 76% | 24% | 89% | 11% | 93% | 7% | 36% | 11% | 21% | 79% |
| 2400 | 12 | 2368 | 32 | 87762 | -57% | 29.4 | -2% | 1.025 | 0.43 | 82% | 18% | 72% | 28% | 83% | 17% | 88% | 12% | 36% | 11% | 21% | 79% |
| 2200 | 12 | 2122 | 78 | 80449 | -60% | 29.4 | -2% | 0.758 | 0.47 | 78% | 22% | 67% | 33% | 78% | 22% | 85% | 15% | 35% | 9% | 19% | 81% |
| 2000 | 10 | 1925 | 75 | 73135 | -64% | 29.3 | -2% | 1.147 | 0.51 | 70% | 30% | 59% | 41% | 67% | 33% | 76% | 24% | 31% | 9% | 16% | 84% |
| 1800 | 13 | 1781 | 19 | 65822 | -68% | 28.7 | -4% | 1.015 | 0.54 | 62% | 38% | 52% | 48% | 56% | 44% | 66% | 34% | 27% | 6% | 13% | 87% |
| 1600 | 14 | 1475 | 125 | 58508 | -71% | 5.4 | -82% | 5.369 | 0.17 | 65% | 35% | 59% | 41% | 10% | 90% | 37% | 63% | 12% | 17% | 3% | 97% |

*Replications in which the productivity deviated significantly from the average productivity in an experiment, were eliminated to reduce the influence of outliers. Outliers were eleminated until a standard deviation of approximately 1 was achieved.

**Policy 3 (balanced)**

| Power constraint | Nr. of replications per experiment* | Measured average peak power | Delta | Yearly contractual power demand related costs | Reduction contractual power demand related costs | Productivity per STS Crane | Reduction productivity per STS crane | Standard deviation productivity* | Load factor | Outcome request for action Trolley Landside | | Outcome request for action Trolley Waterside | | Outcome request for action Spreader Landside | | Outcome request for action Spreader Waterside | | Applied profile | | Total waiting time | | Waiting time landside | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [kW] | [-] | [kW] | [kW] | [€/year] | [-] | [box/hour] | [-] | [boxhour] | [-] | Approved | Denied | Approved | Denied | Approved | Denied | Approved | Denied | Initial | Adapted | Landside | Waterside | AGLV | Platform |
| Infinite (base scenario) | 11 | 5541 | 0 | 202621 | - | 30.0 | - | 1.002 | 0.21 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 39% | 12% | 24% | 76% |
| 4800 | 12 | 4392 | 408 | 175524 | -13% | 30.0 | 0% | 1.361 | 0.24 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 38% | 10% | 20% | 80% |
| 4600 | 13 | 4219 | 381 | 168211 | -17% | 30.1 | 0% | 1.262 | 0.24 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 38% | 11% | 23% | 77% |
| 4400 | 11 | 4056 | 344 | 160897 | -21% | 30.0 | 0% | 1.419 | 0.25 | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 100% | 0% | 38% | 11% | 23% | 77% |
| 4200 | 13 | 3923 | 277 | 153584 | -24% | 30.0 | 0% | 1.018 | 0.26 | 100% | 0% | 99% | 1% | 100% | 0% | 100% | 0% | 100% | 0% | 38% | 12% | 24% | 76% |
| 4000 | 13 | 3743 | 257 | 146270 | -28% | 30.0 | 0% | 1.151 | 0.27 | 99% | 1% | 99% | 1% | 100% | 0% | 100% | 0% | 99% | 1% | 38% | 12% | 22% | 78% |
| 3800 | 14 | 3576 | 224 | 138957 | -31% | 30.0 | 0% | 0.975 | 0.29 | 99% | 1% | 99% | 1% | 100% | 0% | 100% | 0% | 99% | 1% | 39% | 10% | 22% | 78% |
| 3600 | 14 | 3396 | 204 | 131643 | -35% | 30.0 | 0% | 1.127 | 0.30 | 99% | 1% | 98% | 2% | 99% | 1% | 99% | 1% | 99% | 1% | 38% | 12% | 23% | 77% |
| 3400 | 13 | 3231 | 169 | 124330 | -39% | 30.1 | 0% | 1.215 | 0.32 | 98% | 2% | 97% | 3% | 99% | 1% | 99% | 1% | 98% | 2% | 38% | 11% | 22% | 78% |
| 3200 | 14 | 3095 | 105 | 117016 | -42% | 30.0 | 0% | 0.821 | 0.33 | 97% | 3% | 96% | 4% | 98% | 2% | 98% | 2% | 97% | 3% | 38% | 11% | 22% | 78% |
| 3000 | 11 | 2875 | 125 | 109703 | -46% | 30.0 | 0% | 0.888 | 0.35 | 96% | 4% | 94% | 6% | 97% | 3% | 97% | 3% | 96% | 4% | 38% | 12% | 23% | 77% |
| 2800 | 10 | 2690 | 110 | 102389 | -49% | 29.9 | 0% | 1.304 | 0.37 | 95% | 5% | 93% | 7% | 95% | 5% | 96% | 4% | 95% | 5% | 37% | 12% | 22% | 78% |
| 2600 | 13 | 2581 | 19 | 95076 | -53% | 30.0 | 0% | 1.026 | 0.39 | 93% | 7% | 89% | 11% | 93% | 7% | 94% | 6% | 92% | 8% | 37% | 11% | 22% | 78% |
| 2400 | 11 | 2355 | 45 | 87762 | -57% | 29.8 | -1% | 1.076 | 0.43 | 90% | 10% | 84% | 16% | 90% | 10% | 92% | 8% | 89% | 11% | 36% | 9% | 19% | 81% |
| 2200 | 12 | 2183 | 17 | 80449 | -60% | 29.7 | -1% | 0.955 | 0.46 | 87% | 13% | 81% | 19% | 85% | 15% | 88% | 12% | 85% | 15% | 36% | 9% | 19% | 81% |
| 2000 | 12 | 1985 | 15 | 73135 | -64% | 29.3 | -2% | 0.800 | 0.50 | 81% | 19% | 75% | 25% | 79% | 21% | 83% | 17% | 79% | 21% | 35% | 8% | 17% | 83% |
| 1800 | 13 | 1806 | -6 | 65822 | -68% | 27.9 | -7% | 1.169 | 0.53 | 76% | 24% | 66% | 34% | 70% | 30% | 76% | 24% | 72% | 28% | 35% | 9% | 17% | 83% |
| 1600 | 12 | 1633 | -33 | 58508 | -71% | 27.3 | -9% | 0.990 | 0.57 | 69% | 31% | 62% | 38% | 57% | 43% | 66% | 34% | 65% | 35% | 30% | 8% | 16% | 84% |

*Replications in which the productivity deviated significantly from the average productivity in an experiment, were eliminated to reduce the influence of outliers. Outliers were eleminated until a standard deviation of approximately 1 was achieved.