The Effect of Charging Strategies For Battery-Powered Terminal Trucks on the Productivity and Costs of an RTG Container Terminal

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The Effect of Charging Strategies For Battery-Powered Terminal Trucks on the Productivity and Costs of an RTG Container Terminal

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Preface

This is it.

Countless hours, days, and years it has taken me to get to this beautiful moment. I always knew I would make it, just not when. It was a journey with downs but mostly ups. I am proud of what I have achieved and will cherish all that I have learned at TU Delft until my days are numbered.

First, I would like to thank all who have made my time at Portwise such a great experience. All the activities, kroketten, lunch walks, and crazy drinks made my time feel like a party. It might have cost me a couple of extra months, but I could never have expected that we would have so much fun!

Mark Duinkerken, I would like to thank you for your patience with me these last couple of years. I wasn't always your easiest student, but you never gave up on me, and your feedback was always of great help. Your gentle nudges to get my act together and put in some work helped me a lot through the process of this thesis.

I would also like to thank Rudy Negenborn for taking the time to chair my thesis committee. Although our time was often limited, your feedback was insightful and comprehensive with regard to my work.

My biggest gratitude goes out to Manasse Hutte, who has had to deal with me for the last year. Besides being a great daily supervisor, you were an even better friend. The countless games of pool, a couple of losses in chess, and numerous conversations about cycling made every day at work a bit better. Thank you for getting me all the way to the end.

Finally, I would like to thank all my friends and family who have been through the highs and lows. My mum and sister, who have always believed that I could do anything I set my mind to. Marieke, my love, who had to endure most of my outbursts but never stopped helping me get through everything. Dad, I made it. I love you all.

This is it. It is done. Goodbye TU Delft.

H.W.E. Boer
Delft, September 2024

Summary

A changing climate and the effect of global warming are among some of the biggest challenges facing mankind. Consequently, industries have been pushed by international and regional institutions to reduce their greenhouse gas (GHG) emissions and become more sustainable. Electrification of container handling equipment is gaining momentum in a bid to fight global emissions. This deployment is driven partly by emission reduction policies and by energy use cost reductions. Terminal trucks (TTs) are widely used as a means of transporting containers within a Rubber Tired Gantry crane (RTG) terminal. This study focuses on the electrification and charging strategies of battery-powered terminal trucks (BTTs). Charging strategies comprise a combination of charging infrastructure and a charging policy. The charging infrastructure determines how the batteries are physically charged. Charging policies determine when and for how long a battery is charged. A charging strategy has a deep impact on the system performance of a terminal. It is important that the charging of batteries does not negatively affect the overall performance of the terminal. A loss in production could result in higher costs for the terminal operator. To ensure this, a selected charging strategy must ensure little out of operation time for the battery terminal truck, at a reasonable investment cost.

Because it is still an emerging technology, little research has been done into the effect of switching to a battery-powered terminal on terminal productivity. Furthermore, the cost implications of switching to BTTs in RTG terminals are poorly understood, particularly regarding the higher expenses associated with BTTs and the necessary charging infrastructure.

This leads to the research question:

”What is the effect of charging strategies for battery-powered terminal trucks on the productivity and costs of an RTG container terminal?”

This research tests different charging strategies for battery-powered container terminal trucks with the use of a large-scale terminal operation simulation. Using the simulations, the research investigates the effect on the terminal performance of different charging strategies compared to benchmark diesel-powered operations. Alongside this, a cost estimation per strategy is made. A BTT operations model, including charging, is implemented in the TIMESQUARE RTG terminal simulation environment of Portwise. It simulates the operations of driving and charging BTTs within an RTG terminal. Preliminary to the design of these models, a system analysis of the RTG terminal and the BTT itself is conducted, as well as literature research on the charging strategies for all types of battery-powered container handling equipment (CHE).

With the knowledge gathered during the literature study on the different charging strategies for battery-powered CHE, design alternatives for specifically charging BTTs are inventoried and adapted. A design alternative comprises the combination of charging infrastructure type, location, and charging policy. Each design alternative is implemented in the RTG/BTT model.

1. Out of Operations Charging (OOP) The entire fleet of BTTs is recharged during non-operating hours at a parking or depot. It uses a substantial number of wired chargers to charge the BTTs.

2. Centralised Fixed Threshold Charging (CFT) All charging stations are located in one central area in the terminal. The BTTs operate until a predefined threshold value for the state of charge (SoC) is reached. When this SoC is reached, the BTT can no longer accept a new container handling job and is ordered to report to one of the available charging stations.

3. Decentralised Fixed Threshold Charging (DFT) Several charging stations are positioned at strategic locations throughout the terminal. Same charging policy as CFT.

4. Decentralised Pre-Emptive Charging (DPE) Same charging station location. The charging threshold for the BTTs is dynamic and continuously determined based on the SoC of all BTTs in the fleet.

5. Decentralised Opportunity Charging (DOP) At every RTG a wireless fast-charging charger is installed, to enable the charging of BTTs. The charging is simultaneous with the loading and unloading of containers at RTG.

To test the performance of the different charging strategies the Key Performance Indicator (KPI) of QC productivity is used. This number indicates the average number of containers moved per QC per hour. It is often the most important performance indicator for a terminal and critical to ensure that a strategy can perform at a required performance level. Furthermore, it serves as a means of comparing different strategies.

A set of experiments is conducted to test the performance of the different charging strategies in varying configurations and charger numbers. Results are compared to the benchmark of an RTG terminal with diesel-powered TTs.

When employing strategies such as Out of Operation and Decentralised Opportunity Charging, BTT charging does not negatively impact terminal productivity with a QC productivity of 25.73 box/hr and 25.72 box/hr respectively. The performance metrics for these strategies are statistically comparable to those of terminals utilising the same number of diesel-powered terminal trucks (25.71 box/hr).

However, with charging during container handling operations additional vehicles are needed, due to the downtime required for charging, leading to the need for supplementary vehicles to maintain performance similar to a smaller fleet of diesel-powered terminal trucks. The study also highlights that while the location of charging stations provides a slight, though not statistically significant, improvement in QC productivity of 0.22 box/hr. A limited number of charging lanes, results in increased waiting on charging times. This, in turn, reduces BTT availability and adversely affects QC productivity.

The implementation of a decentralised pre-emptive charging strategy with a dynamic charge threshold emerges as a promising strategy, as it minimises charge waiting times and BTT idle periods, thus enhancing QC productivity (strategy average of 25.89 box/hr) whilst also stabilising charge lane utilisation. Conversely, central charging with a fixed threshold and limited charging lanes strongly impairs QC productivity. Increasing the number of available charge lanes decreases this.

Despite the higher upfront vehicle and infrastructure investments required, battery-powered terminal trucks offer the advantage of lower operational costs over their lifetime compared to diesel alternatives. Particularly, out of operations charging is the most cost-effective strategy at €49.6M, provided the terminal has sufficient downtime to accommodate simultaneous vehicle charging. On the other hand, decentralised opportunity charging incurs the highest costs of the battery-powered configurations at €55.3M. This is primarily due to the substantial investment needed for high-capacity wireless charging infrastructure.

Taking both QC productivity and total cost into consideration, the study concludes that decentralised pre-emptive charging with a large number of charge lanes is the optimal strategy. This approach not only statistically significantly outperforms some diesel benchmarks in terms of QC productivity, at 26.31 box/hr, but also has a low total cost, €51.3M, by maximising operational efficiency and minimising operating expenses. Thus, for RTG-based terminals aiming to balance productivity with cost-effectiveness, this strategy stands out as the most viable and advantageous solution.

The RTG/BTT model and subsequent simulations developed during this research were able to simulate the operations of battery-powered terminal trucks, including charging within the RTG terminal. It serves as a good basis for testing the effect of different charging strategies, although it has some shortcomings. Little statistically significant difference between charging strategies was observed, this could be because the charging strategies alone did not have a substantial effect on terminal performance as tested in the current set-up of the RTG terminal model. The productivity of the QC was also susceptible to congestion within the terminal not necessarily caused by a charging strategy.

Furthermore, due to the absence of real-life data on energy consumption and equipment cost it is difficult to confirm the validity of the results as presented in this research. A different energy consumption could present large implications on the effectiveness of one of the proposed charging strategies.

Based on this thesis, further research is recommended to optimise charging strategies for battery-powered terminal trucks (BTTs):

- Exploring larger terminal layouts to assess the impact of travel distance terminal performance
- Testing charging strategies in real-life RTG terminal setups to better understand costs and practical implications.
- Investigating the relationship between battery size, charger capacity, and operational time.
- Developing dynamic charging strategies, such as adjusting charging to match quay work demand and task dependant opportunity charging.

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Nomenclature

Abbreviations

Abbreviation	Definition
TT	Terminal Truck
BTT	Battery-Powered Terminal Truck
RTG	Rubber Tired Gantry Crane
QC	Quay Crane
XT	External Truck
AGV	Automated Guided Vehicle
KPI	Key Perfomance Indicator
QCR	Quay Crane Rate
CS	Charging Station
CL	Charge Lane
OOP	Out of Operations
CFT	Centralised Fixed Threshold
DFT	Decentralised Fixed Threshold
DPE	Decentralised Pre-Emptive
DOP	Decentralised Opportunity

1 Introduction

A changing climate and the effect of global warming are among some of the biggest challenges facing mankind. Consequently, industries have been pushed by international and regional institutions to reduce their greenhouse gas (GHG) emissions and become more sustainable. This is also true for the shipping and transportation industry. Unfortunately, the environmental impact the shipping of containers has does not stop when container vessels enter the port. The equipment used in ports is often powered by diesel or diesel hybrid engines, resulting in local air pollution. In 2010 Dutch research institute, TNO estimated that per Twenty Foot Equivalent Unit (TEU), a standard container size, handled within Dutch container terminals, 4,5 litre diesel was needed [1]. Electrification of heavy-duty equipment is gaining momentum in a bid to fight global emissions. This deployment is driven partly by emission reduction policies and by energy use cost reductions [2]. Tethered container handling equipment can be powered by cable or bus bar. Batteries will power free-roaming equipment pieces. These batteries need to be charged or swapped when empty. This study focuses on the electrification and charging strategies of battery-powered terminal trucks (BTTs). Terminal trucks are widely used as a means of transporting containers within a terminal. Effectively switching to battery power for terminal trucks could aid in cutting down GHG emissions and make container terminals more sustainable.

Section 1.1 introduces the problem statement that functions as the motivation for this research. Section 1.2 describes the research objective. In section 1.3 the main research question is stated. This main research question is answered using sub-questions that are subsequently presented in this section. In section 1.4 the research methodology is discussed.

1.1. Problem statement

The adoption of battery-powered terminal trucks holds significant potential for creating more sustainable and environmentally friendly container terminal operations, but current implementation is lacking. Unlike fleets of diesel-powered trucks commonly seen in terminals, battery-powered counterparts remain in the pilot phase. Several challenges contribute to this limited adoption.

Firstly, the upfront costs of acquiring battery-powered terminal trucks are notably higher than their diesel counterparts. This cost extends beyond the vehicles themselves, encompassing the establishment of specialised charging infrastructure. Such infrastructure demands significant investment, deterring widespread adoption.

Moreover, the absence of intelligent charging strategies further complicates the transition. Current practices often involve charging vehicles only when their battery levels drop below a certain threshold. This approach leads to operational downtime as trucks await charging, necessitating additional vehicles to compensate for lost productivity.

Effectively managing the charging strategies of battery-powered terminal trucks is paramount to unlocking their full potential. Intelligent charging protocols can enhance energy efficiency, reduce downtime, and ultimately lower operational costs. As the industry continues to grapple with these challenges, investigating different possible charging strategies remains a critical focus for realising the economic and environmental benefits of battery-powered solutions in container terminals.

1.2. Research objective

Following the problem statement it is evident that investigating, adapting and testing different charging strategies can be beneficial to the implementation of battery-powered terminal trucks. This research will further explore the potential benefits and challenges associated with the implementation of charging as part of the overall terminal operations.

This thesis aims to test different (intelligent) charging strategies for battery-powered container terminal trucks with the use of a large-scale simulation. Using the simulations, the research will investigate the feasibility of adopting different charging strategies.

The research objective of this thesis can be summarised as follows:

"Inventory, adapt and model different charging strategies for battery-powered terminal trucks and test these strategies in a large-scale RTG terminal operation simulation."

The performance of the different charging strategies will be tested with key performance indicators (KPIs) such as Quay Crane Rate (QCR) and investment and operational costs associated with implementing different charging strategies.

The Quay Crane Rate, or QC productivity, is the average number of containers handled by a quay crane per hour and is a critical KPI in assessing terminal efficiency. By implementing various charging strategies for terminal trucks, the impact on QCR can be observed. Strategies that minimise BTT downtime due to charging interruptions can lead to potentially increasing the QCR by reducing overall operational downtime.

1.3. Research questions

An academic investigation is developed based on the stated research objective outlined in Section 1.2. This study attempts to answer the main research question by breaking it down into several sub-questions.

Main research question

The main research question of this thesis has been formulated as follows:

"What is the effect of charging strategies for battery-powered terminal trucks on the productivity and costs of an RTG container terminal?"

Sub-questions

The following sub-questions aid in answering the main research question.

1. What activities and functions are performed within container terminals?
2. What are the characteristics and operational profile of battery-powered terminal trucks?
3. Which charging strategies for battery-powered vehicles are proposed in the literature?
4. What are possible design alternatives for charging battery-powered terminal trucks?
5. How can the operation of a container terminal, including the operational profile and charging of battery-powered terminal trucks, be represented by a model?
6. How can the different charging strategies be implemented and tested in a terminal operation simulation model?
7. How do the different charging strategies, both in configuration and operation, perform?
8. How do the productivity and cost of different charging strategies compare to diesel-powered RTG terminals?

1.4. Methodology

During the thesis work the different sub-questions are answered to find a conclusive answer to the presented research question. To do this several methods are used.

System analysis

The first part of this research will focus on the system analysis of the container terminal and the battery-powered terminal trucks. The different activities, infrastructure and interactions will be described. Furthermore, the characteristics and operational profile of the battery-powered terminal trucks are introduced. The first two sub-questions will be answered: *What activities and functions are performed within container terminals?, What are the characteristics and operational profile of battery-powered terminal trucks?*

Literature Review

After the system analysis a clear understanding of the workings of the container terminal and the battery-powered terminal trucks will be established. Next, during the literature review of this research, the third and fourth sub-questions will be answered:*Which charging strategies for battery-powered vehicles are proposed in the literature?* ,*What possible design alternatives can be implemented for charging battery-powered terminal trucks?* During this process, various strategies specifically for charging battery-powered vehicles will be investigated and adapted. Examples of charging methods presented in the literature will be modified to suit battery-powered terminal trucks.

Modelling

During the modelling phase of the research the sub-question: *How can the operation of a container terminal, including the operational profile and charging of battery-powered terminal trucks, be represented by a model?* Will be answered. With a model describing the operations and charging of the terminal trucks, the different charging strategies can be tested in the simulation stage, which will follow after this. To add these functionalities the operational profile of the battery-powered terminal trucks needs to be modelled in combination with the different charging strategies. This will be done using available performance characteristics of these vehicles and chargers provided by terminal truck manufacturers and information publicly available.

Evaluation

The last part of the research will be focused on implementing the developed charging strategies in the model of Portwise and testing the different proposed charging strategies. The functions and charging of battery-powered terminal trucks will be added to the large-scale terminal operation simulation model. With this simulation model the different charging strategies will be tested and the performance compared to each other. The final three sub-questions will be answered:*How can the different charging strategies be tested in a terminal operation simulation model?, How do different charging strategies, both in configuration and operation perform?, How do the productivity and cost of different charging strategies compare to current diesel-powered RTG terminals?*

2
Container terminals and battery-powered terminal trucks

This chapter sets out to answer the first sub-questions: *What activities and functions are performed within container terminals?* and *What are the characteristics and operational profile of battery-powered terminal trucks?* It starts by providing a general introduction to the role container terminals play within the supply chain network of global commerce. Next, the RTG terminal and its components are discussed. Finally, the battery-powered terminal truck and its characteristics are introduced.

2.1. Container terminal

Container terminals play a crucial part in the supply chain network. The main role of container terminals is to connect deep-sea transport with other modes of transport. The terminals act as a distribution node for transporting cargo between producers and end-consumers. Most terminals function as locations where containers are loaded and unloaded from deep-sea vessels onto smaller (feeder) vessels, barges, trucks and trains. Carlo, Vis, and Roodbergen [3] describe the functions and layout of a container terminal. Within a terminal three primary functions are completed: Transfer (lift and place), transport and storage of containers. Container terminals can be divided into five main areas. The three primary sections of container terminals are the quay, (storage) yard, and (terminal) gate. At the seaside containers are loaded and unloaded by cranes that lift and place (transfer) containers between the vessels and the quay. Connecting the seaside and the storage is the transport area. In this area, a variety of horizontal transportation vehicles operate whose function is to move containers between the yard and quay and vice versa. This (storage) yard is made up of several lanes where containers can be stored for an amount of time. From the yard, containers are loaded onto different modalities. Trucks that deliver and pick up containers pass through the gate. Barges can be handled alongside deep-sea vessels at the quay, while some terminals have dedicated quays for barges. Finally, container terminals frequently include a rail terminal where containers are loaded or unloaded from rail carts pulled by locomotives. One of the most common types of container terminals is the terminal that utilises terminal trucks and rubber tired gantry cranes, often called an RTG terminal.

2.2. Components of an RTG terminal

The terminal type that is central to this research is the RTG terminal. In an RTG terminal containers are handled by different types of container handling equipment (CHE). An RTG terminal, like any type of container terminal, is often divided into three main areas of operation. Figure 2.1 shows a schematic of a typical RTG terminal with the different areas from quayside to landside. Containers can enter and leave the terminal from both sides. Import containers arrive by vessel at the quay and depart by external truck, whereas export containers reverse this process. Containers are stored in the storage yard between their arrival and departure.

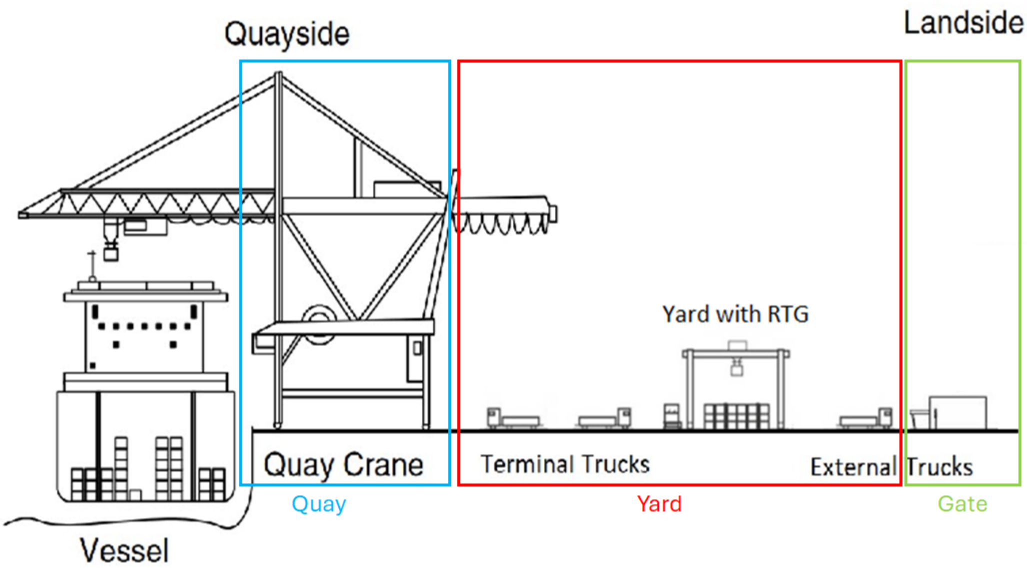


Figure 2.1: Three main areas of an RTG terminal

2.2.1. Quay Cranes

At the quay, Quay Cranes (QCs) operate. These cranes also referred to as ship-to-shore cranes (STS), load and unload vessels. The containers are delivered to and collected from the QCs by terminal trucks. The most common type of QC in RTG terminals is the single trolley QC. Presented in Figure 2.2 the three axes of motion of the QC are evident. Along the quay, the QC can travel to line up with the correct bay in the vessel. Once it reaches the correct bay the trolley traverses over to the vessel and the container is hoisted up or down above the vessel.

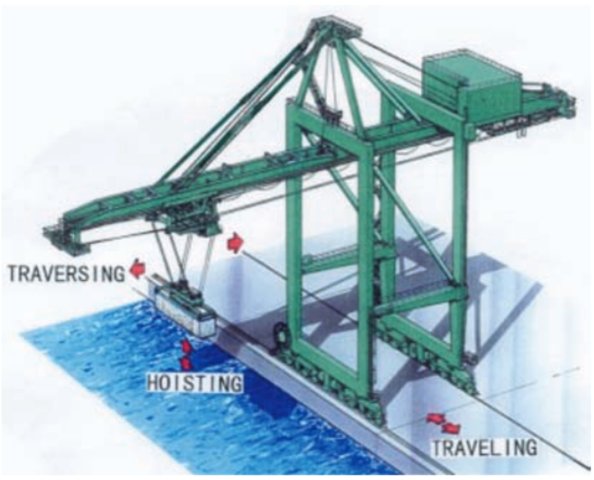


Figure 2.2: Single Trolley Qauy Crane [4]

QCs can operate in a variety of configurations, but each operation requires a different type of spreader. The QC lifts a single 20- or 40-foot container during the single lift operation (Figure 2.3 (a,b)). The twin lift operation allows the QC to lift two 20-foot containers end-to-end (Figure 2.3 (c)). The tandem lift operation allows the QC to lift two 20-foot containers, two 40-foot containers, or four 20-foot containers (Figure 2.3 (d,e,f)).

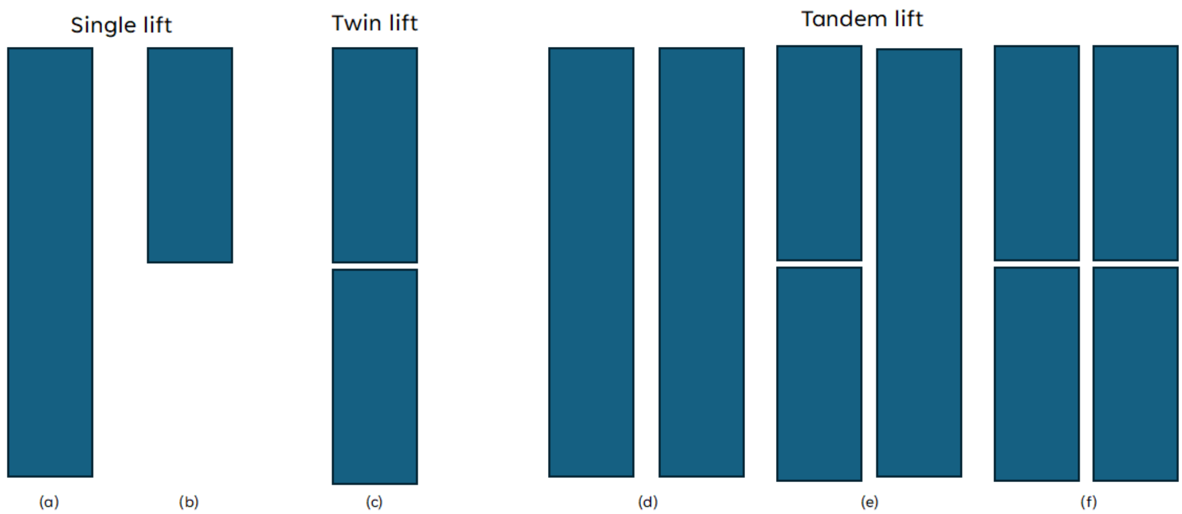


Figure 2.3: QC lift configurations

2.2.2. Terminal trucks

According to Stojaković and Twrdy [5], Terminal Tractors or Terminal Trucks (TT) are globally one of the most used pieces of equipment for horizontal transport of containers. The terminal trucks transport containers on a trailer between the quay and the yard. TTs shuttle containers between the QC at the quay and the RTG in the storage yard. They are also used to transport damaged, extraordinary handling and out-of-gage containers to specialised locations at the terminal. The TTs only operate within the terminal and are operated by drivers who work in shifts. These terminal trucks are almost exclusively diesel-powered, causing large CO_2 emissions.

Some alternatives utilising batteries as the power source are being implemented more frequently, some examples will be described shortly.

2.2.3. Rubber Tired Gantry cranes and storage yard

Rubber Tired Gantry cranes (RTGs) are wheeled mobile gantry cranes, used in terminal operations to store containers in the stack. Horizontal transportation vehicles, predominantly terminal trucks, transfer containers between the RTG and the quay. The RTG drives over the stacking module, consisting of multiple rows and bays. When the RTG reaches the correct bay a transfer of container is made, it never travels over the stack with a container. The benefit of using RTGs for handling containers in the yard is the ability to move the crane between different stack modules. The RTG can exit one module and drive to another module to continue operations. This ensures high productivity and a low number of idle vehicles[6].

Figure 2.4: Rubber Tired Gantry Crane [7]

2.2.4. External Trucks and Gate

The gate serves as the crucial link between the terminal and the hinterland, facilitating the pass trough of external trucks (XTs). These XTs enter the terminal to either pick up one or multiple import containers or drop off one or multiple containers intended for export. Upon arrival at the gate, XTs are required to register, receive instructions regarding their destination within the terminal, and undergo visual inspections of containers for any defects or abnormalities. The XTs pull trailers that are capable of transporting containers in different configurations. An XT can haul one 20-foot container, one 40-foot container or two 20-foot containers combined.

2.2.5. Container flow

Containers, regardless if they are bound for import or export, move through the RTG terminal by the different CHE. Figure 2.5 gives a visual representation of the journey a container completes when being handled at the terminal. For an export container, its journey begins at the gate where the XT enters and drives to its designated RTG ready for transfer, illustrated in yellow. Here the RTG picks up the container and stores it in the yard. When the container is ready to be transported to an outgoing vessel, a TT picks up the container from the RTG which places the container on its trailer. The TT drives in between the stacks in the yard towards the designated QC, illustrated in blue. Here the QC loads the container onto the correct spot on the outgoing vessel. The journey of an import container is similar. The QC picks up the container from the hold or deck of the unloaded vessel and sets it on the trailer being pulled by a TT. The TT drives the container to the designated RTG, which picks it up and transfers it to the stack, illustrated in green. The final step is performed when an XT comes to collect the outgoing container. It picks up the container at the RTG and leaves the terminal trough the gate, illustrated in red.

Figure 2.5: The flow of a container through an RTG terminal

2.3. Terminal Control

The path a container takes from the time it enters the terminal to the time it exits the terminal is globally described in the preceding section. However, the transfer of containers involves far more intricate procedures. This section provides a more thorough discussion of every planning and control procedure that occurs in an RTG container terminal. The different processes work in tandem to streamline operations at the terminal.

2.3.1. Berth planning

Berth allocation, or berth planning, is the process of assigning vessels to specific berths. Vessel arrival information is known ahead of time, usually a few days for small vessels and sometimes months for large container ships [8]. The berth planning process begins as soon as arrival information is available and is continuously updated. When assigning a berth, the berth planning considers the ship's size as well as the length of the berths. Other factors taken into account include the berthing time, future vessel arrivals, and the availability of terminal staff and equipment.

2.3.2. Stowage planning

The foundation for container vesssel planning is stowage planning. The stowage planning determines where containers are positioned on a vessel during a trip. The shipping line handles the initial step of making this planning. Every port a vessel visits during its trip must be included in the shipping line's stowage plan. A shipping line's stowage planning typically works with categories of containers rather than individual containers denoted by numbers. The discharge port, weight or weight class of containers and container length or type are these categories or attributes. Certain positions within the ship are designated for containers with these attributes[8]. Before a vessel arrives at a terminal, the stowage plan is provided to the terminal operator. With this storage plan, the terminal operators know where certain groups of containers are situated on the vessel when unloading and where groups of containers need to be positioned during loading.

2.3.3. Container Allocation

The procedure that determines a container's position in the storage yard is called container allocation or yard planning. The allocation of containers is based on several variables, including the port of destination (POD), the shipping line, the location of import and export containers, the weight of the container, and whether or not this information is known ahead of time. Import container arrival information is frequently available ahead of time, much like vessel arrival information. However, the arrival information for export containers is only available the minute the XT arrives at the terminal. As a result, when an export container arrives at the terminal, a choice is made on where it will be stored[9].

2.3.4. Equipment Allocation

Equipment allocation or logistic planning is the process in which the different types of equipment that operate in the yard and quay are allocated. The allocation determines how many RTGs are needed at each block, at which moment RTGs are transferred to another block to assist in loading or unloading, how many TTs are required in the yard, which TTs service which QC, how many TTs serve each QC, which routes the TTs follow, and the precise number of QCs that operate simultaneously on one ship.

2.3.5. Terminal Operating System

A central control system, often called the Terminal Operating System (TOS), manages all the previously mentioned processes. Within this (computer) operating system, the different plannings and allocations are combined to manage all processes on the terminal. The status of all equipment, containers and vessels is monitored and operational decisions are made. Figure 2.6, shows a schematical overview of how the different processes share information, provide feedback and interact.

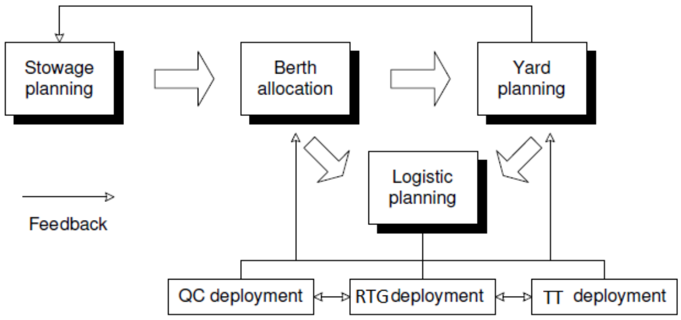


Figure 2.6: Hierarchical control structure in container RTG terminals [9]

2.4. Performance Indicators Container terminals

The performance of any terminal type, whether an RTG terminal or not, is measured using several Key Performance Indicators (KPIs). As described in chapter 1 the most important is often the number of containers moved by the cranes at the quay. This QC productivity is the total number of containers a QC loads or unloads from a vessel per hour [10]. The QC productivity is an important performance measure because it provides a good indicator of the number of containers entering and leaving the terminal. This QC productivity is affected by several external and internal factors. If the ship and QC would operate solely together the productivity relies solely on the maximum trolley and hoist speed of the QC. However, the efficiency of loading and unloading operations also depends on the terminal trucks that deliver or collect the containers. If a QC has to wait for a TT to pick up or drop a container this affects the performance. The TT status indicates whether a truck is actively moving containers or has to wait for an operation. This waiting includes queueing behind other trucks at an RTG or QC, handling time at RTG and QC and for electric vehicles time spent charging and waiting on available chargers.

2.5. Battery-powered Terminal Trucks

This research focuses on the implementation of battery-powered terminal trucks at RTG terminals. Due to rising concerns regarding emissions from diesel trucks at terminals, a switch to battery-powered types is imminent.

Geerlings and Van Duin [11] presented a way of calculating the CO_2 emissions of various diesel-powered equipment in container terminals. TTs consume approximately 4 litres of diesel for every driven kilometre. With this, the authors estimated that the CO_2 emissions of TTs in medium-sized container terminals could be roughly 3 kilograms of CO_2 per container handled.

Yu, Ge, Chen, *et al.* [12]'s research into the CO_2 emissions of terminal tractors further adds to this stating that the pollution by this type of equipment is one of the main sources of pollution in maritime transport.

Simpson, Asce, Thiessen, *et al.* [13] present a solution in the form of battery-powered terminal trucks. Complementing this idea the work of Mohr, Kastner, and Jahn [14] investigates the importance and challenges of deploying battery-powered terminal trucks (BTTs) in container terminals. Both papers agree that the implication of employing battery-powered terminal trucks on a large scale is finding the correct charging strategies and the best positioning approach for charging stations. Although still challenging, all authors agree that due to the rise of diesel costs and the need to cut down on emissions, batteries are the way to go for terminal tractors.

Responding to this shift towards more sustainable solutions, manufacturers of container terminal vehicles are increasingly coming up with battery-powered variants of terminal trucks [15][16][17]. The first battery-powered terminal trucks are slowly deployed at various terminals in the world [18][19]. Figure 2.7 shows a typical battery-powered terminal truck and Table 2.1 provides some basic characteristics of available models at different manufacturers.

The battery-powered terminal trucks have a similar operational profile to a standard diesel-powered one. They operate continuously, transporting containers between the RTG and the yard and the QC at the quay. Battery-powered variants require a high-energy capacity battery to ensure operation for long periods. During accelerating and constant driving electrical energy is used from the batteries, whilst decelerating some energy can be regenerated resulting in some recuperated energy.

Figure 2.7: Battery-powered Terminal Truck[20]

Manufacturer	**Terberg**	**Kalmar**	**TICO**	**Gaussin**	**Sany**
Model ID	YT200EB	TX22	Pro Spotter Electric	APM 75T	SM4600TOBEV
Battery recovery mode	Charge	Charge	Charge	Charge/Swap	Charge
Battery type	LFP	NMC	NMC/NCA	*	LFP
Battery capacity (kWh)	350	112 or 224	132	195/126	282
Operating period (h)	10	12 or 22	*	*	18
Charging period (h)	1	1 or 2	1	*	1.17
Charger Power (kW)	350	*	150	*	350
Motor Power (kW)	300	*	350	*	240

* unknown

Table 2.1: Characteristic Battery-Powered Terminal Trucks

2.6. Charging infrastructure

Different types of charging infrastructure can charge the battery-powered terminal trucks. The charging of the battery is done either externally or internally. Historically battery-powered container handling equipment (e.g. Automated Guided Vehicles) was replenished with battery power by swapping the batteries for a fully charged one. This process required a large amount of spare batteries and battery swapping stations. This technology was used because the lead-acid batteries required a long charging period. Swapping ensured only a minor loss in production [21]. With the development of lithium-ion batteries, that offer high energy density and the ability for fast charging, the effectiveness of externally charging the batteries decreases. Rijsenbrij and Wieschemann [22] describe how charging the lithium-ion batteries in the vehicle is more beneficial in terms of vehicle downtime due to its shorter charging time compared to lead-acid. Complementary to this the authors Xiang and Liu [23] showed in their research that in-vehicle charging becomes more cost-effective when the spare batteries are expensive. This holds when battery-powered equipment is powered with large expensive lithium-ion battery packs.

2.6.1. Wired stationary charging

One option for charging battery-powered terminal trucks is to use wired stationary chargers at charging stations (CS) which have to be installed within the container terminal. The BTT is charged via a conductive connection. The BTT has to park at a CS after which a charging cable is connected through a charging port on the side of the BTT. Figure 2.8 shows a BTT being connected to one of the two charging cables available at the charging station. During charging the BTT remains idle and is unavailable for operations. The vehicle's battery capacity determines the charging duration, required charging power and adopted charging strategy. To achieve acceptable out-of-operation times an adequate number of chargers is needed. This often results in a large number of chargers scattered across the terminal.

Figure 2.8: Battery Terminal Truck Charging station [24]

Various wired stationary charging options exist for battery-powered trucks based on fleet size, energy consumption, and operation type. Charging options include slow alternating current (AC) with power below 43 kW, as well as fast and ultra-fast direct current (DC) charging with power up to multiple MW (still under development)[25]. A summary of the different wired charging types available is given in Figure 2.9.

Charger type	Nominal power output	Charging standard	Location	Estimated charging times
Overnight	50–150 kW DC	Combined Charging System (CCS) or CHAdeMO	Depot, public parking space	8 hours
Opportunity fast	150–350 kW DC		Public charging station, depot, destination location	0.5 hours
Opportunity ultra-fast	750 kW–3 MW DC	Megawatt Charging System (MCS) or ChaoJI	Public charging station, depot, destination location	0.5 hours

Figure 2.9: Summary of wired stationary charging options[25]

2.6.2. Inductive charging

Another type of charging infrastructure is inductive charging. The benefit of this type of infrastructure is the absence of any above-ground equipment. A vehicle drives over coils embedded within the terminal surface and begins charging. A critical flaw of the inductive charging system is its low energy efficiency, resulting in extra charging costs. According to Liu and Song [26] applications of this have successfully been developed for city buses that drive pre-established routes. This technology could be adapted to be suited for implementation within container terminals.

The first manufacturers have started pilots with this technology. A fleet of battery-powered terminal tractors is being charged with this technology at the Port of Los Angeles. The charging power is up to 500 kW. A BTT is anticipated to be fully recharged at this power level in less than 15 minutes. It is imperative that the battery pack is capable of ultra-fast charging and is relatively small, about 125 kWh. [27][28].

Figure 2.10: Wireless charging Battery Terminal Truck [28]

2.6.3. Current collector devices

The final infrastructure not yet described in this research is the current collector or pantograph. A technology that is often found on trains. Electric current collectors are typically made up of one or more spring-loaded arms that press a collector or contact shoe against a rail or overhead wire. The vehicle drives to a charging station equipped with a conductive pad. When the vehicle is in place the current collector is automatically extended and once contact is established, charging commences[29]. The benefit of this system is that it is a well-developed technology in other fields and easily adapted to work in terminal operations. The downside is the need for a current collector at a height, above the vehicle. This will result in more possibilities for interference with other operations.

The first implementations of this technology in container terminals were introduced at the end of 2023. In the Port of Long Beach, California a fleet of 33 new battery-powered terminal trucks is charged by the same number of 175kW DC chargers via an electric receptacle installed at the truck depot. All vehicles are charged at night. This results in no operational loss, but requires significant infrastructure investment[30].

Figure 2.11: Current collector charging Battery Terminal Truck [30]

In Table 2.2, the different charging technologies are summarised, benefits and challenges are discussed and relevant references are provided.

Charger Technology	Charging Power	Benefits	Challenges	References
Wired Stationary	Overnight: 50 - 150 kW Fast: 150 - 350 KW Ultra Fast: 350 - 3 MW	Well developed technology easy to implement in the terminal Ability to deliver very high charging powers	Need to physically connect cable to vehicle	[24],[25]
Wireless	500 kW	No above-ground infrastructure	Low energy efficiency, high cost	[26],[27],[28]
Current Collector	175 kW	Well developed technology easy to implement in the terminal	Often installed above vehicle, resulting in possible obstruction of operations	[29],[30]

Table 2.2: Charging technologies for Battery Terminal Trucks

2.6.4. Charging infrastructure cost

The cost of various charging infrastructures is largely determined by the required charging capacity. Higher capacity or power demands result in higher infrastructure costs. Additionally, the annual operational expenses to maintain the infrastructure in working condition also rise with the required charging capacity. Figure 2.12 provides some cost estimations for different charging capacities. These are estimations for public chargers but serve as a good estimation for charging infrastructure that could be installed at terminals.

Public charger power	Hardware and software	Planning	Installation	Total upfront costs (hardware and software, planning, and installation)	Operation and maintenance per year
Public 50 kW DC	€28,125	€1,350	€15,200	€44,700	1.2%*28,125 = €340/year
Public 150 kW DC	€70,000	€3,645	€18,000	€91,700	1.2%*70,000 = €840/year
Public 350 kW DC	€170,000	€7,655	€54,000	€231,700	1.2%*170,000 = €2,040/year
Public 1 MW DC	€440,000	€21,800	€154,000	€615,800	1.2%*440,000 = €5,300/year

Figure 2.12: Cost estimation of different charger capacities [25]

2.7. Conclusion

This chapter began with an overview of the role container terminals played in the global supply chain network. Following this, the components and operations of the RTG terminal were discussed. Finally, the chapter introduced the battery-powered terminal truck, detailing its operational profile and charging infrastructure. Sub-questions 1 and 2 were answered.

1. *What activities and functions are performed within container terminals?*

Container terminals are vital in the supply chain network, linking deep-sea transport with other transportation modes and serving as distribution nodes between producers and consumers. These terminals primarily function to load and unload containers from deep-sea vessels onto feeder vessels, barges, trucks, and trains. There are three key functions within a terminal: transferring (lifting and placing), transporting, and storing containers. Container terminals consist of three main areas: the quay, storage yard, and terminal gate. Cranes at the seaside load and unload containers between vessels and the quay, while various horizontal transportation vehicles move containers between the yard and the quay in the transport area. The yard contains lanes for container storage, from where they are loaded onto different transport modes. External Trucks pass through the gate to pick up and deliver containers, and barges can be handled alongside deep-sea vessels at the quay or dedicated barge quays. Additionally, many terminals feature a rail terminal for loading and unloading containers from trains. A common type of container terminal is the RTG terminal, which uses terminal trucks and rubber tired gantry (RTG) cranes.

2. *What are the characteristics and operational profile of battery-powered terminal trucks?*

Battery-powered terminal trucks operate similarly to diesel variants, with the key difference being that they are powered by an internal battery that needs to be charged when depleted. During accelerating and constant driving electrical energy is used from the batteries, whilst decelerating some energy can be regenerated resulting in some recuperated energy. Charging can be done at several types of charging infrastructure. The chargers are either wired, inductive or use a conductive contact pad. Different manufacturers produce types of BTTs with varying motor powers and battery capacities. A larger battery capacity with a low motor power ensures longer operation periods. Table 2.1 and Table 2.2 provide summaries of the characteristics of different battery-powered terminal trucks and charging infrastructure options.

3

Charging strategies

In this third chapter charging strategies for battery-powered container terminal equipment are discussed. First sub-question 3: *Which charging strategies are proposed in the literature?*, will be answered using a literature study. With this knowledge sub-question 4:*What are possible design alternatives for charging battery-powered terminal trucks?*, will be answered and several design alternatives will be presented.

3.1. Charging strategies

Charging strategies comprise a combination of charging infrastructure and a charging policy. The charging infrastructure determines how the batteries are physically charged. Charging policies determine when and for how long a battery is charged. A charging strategy has a deep impact on the system performance of a terminal. It is important that the charging of batteries does not negatively affect the overall performance of the terminal. A loss in production could result in higher costs for the terminal operator. To ensure this, a selected charging strategy must ensure little out-of-operation time for the battery terminal truck, with reasonable investment and operational costs.

3.2. Charging strategies from literature

Several researchers have investigated different charging strategies for battery-electric vehicles. Some of their work is discussed in this research. The works presented are limited to research on battery-powered container equipment operating in container terminals.

3.2.1. Non-Operating Hours Charging

The work of Simpson, Asce, Thiessen, *et al.* [13] presents the charging policy of in-vehicle non-operating charging. This first strategy uses non-operating hours to recharge batteries and uses the energy obtained to run a full operating shift. Many charging locations, which are heavily used during non-operating periods, will be needed for this strategy. Additionally, this strategy might require larger batteries, increasing the equipment's initial cost. Research by Mohr, Kastner, and Jahn [14] into charging BTTs adds that this strategy is only effective in smaller container terminals with a small fleet of vehicles and a single shift per day. This *single-shift operation* depends on the ability of the fleet to contain enough battery capacity to operate the full shift.

3.2.2. Fixed Threshold Charging

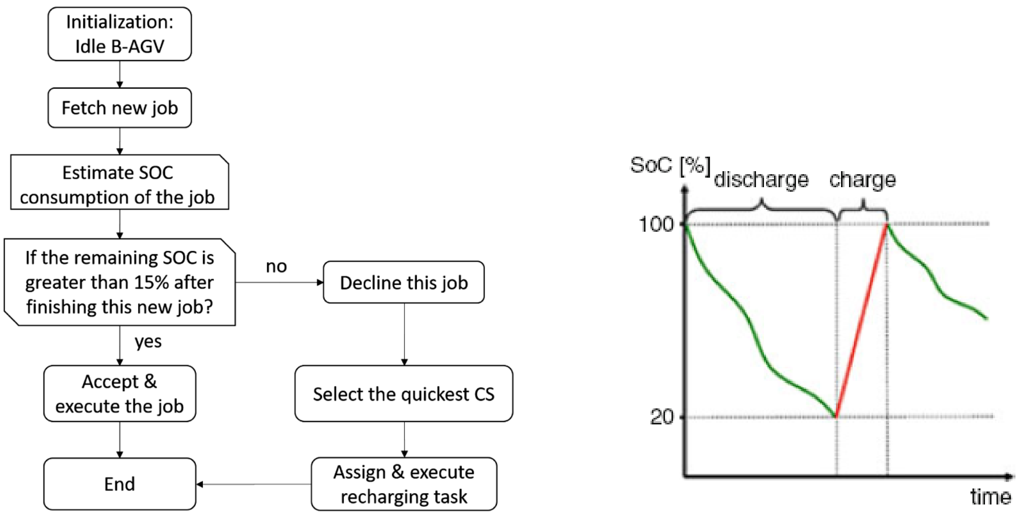
As the authors Sun, Zhai, Li, *et al.* [31] describe in their work, for larger more advanced terminals non-operating charging is not a viable option. At these terminals, operations are often 24/7 with vehicles operating in multiple consecutive shifts. During a shift, the battery level of battery-powered equipment will become insufficient and energy replenishment is needed. A possible charging policy is a fixed threshold policy. With the fixed threshold charging policy, battery-powered vehicles are ordered to charge when the state of charge (SoC) reaches a predefined percentage of the total battery capacity.

Charging is done at a charging station (CS) with conductive chargers. To ensure enough operational capacity extra vehicles are to be acquired.

According to Simpson, Asce, Thiessen, *et al.* [13], the idea is to charge extra equipment during periods when the rest of the fleet is operational. Assuming a charging-to-operating ratio of 1:4, this would lead to a 25% increase in fleet size. Compared to the non-operating strategy, this strategy reduces the number of charging stations while requiring additional equipment. However, convenient switching between operating and charging equipment is required for fluid and continuous operation with minimal interruptions.

The work by authors Ma, Zhou, and Stephen [32] on charging battery-powered AGVs discusses the control structure within the terminal operating system (TOS) for the fixed threshold strategy. Figure 3.1a shows a diagram of the decisions that are taken to establish which Automated Guide Vehicles (AGVs) must be charged and where. When a new job is assigned to an AGV, its SoC is checked first. If the SoC drops below a predetermined level (in their work 15%) after completing the new job, the job is declined and the AGV is sent to one of the charging stations. The quickest charger is selected. The quickest charger is not necessarily the one closest to the vehicle. The charging period and lost time in driving distance are checked for every available charger. The one which results in the lowest amount of lost time is selected. When the AGV arrives at the CS a cable is automatically plugged into the side of the vehicle and charging commences. The battery is fully charged, after which the AGV is put back in service. Figure 3.1b shows how the SoC over time changes during a discharging cycle and a charging cycle.

Mohr, Kastner, and Jahn [14] describe a similar strategy for charging BTTs at an RTG terminal. When the SoC of the BTT reaches a critical level, the worker drives to a depot where fully charged vehicles are stationed. The driver swaps the empty BTT for a full one and continuous operation. This ensures very little to no loss in production but requires a large number of spare vehicles and chargers.



(a) Control loop [32]

(b) SoC[22]

Figure 3.1: Control loop and SoC for threshold charging

3.2.3. Opportunity Charging

The work by Simpson, Asce, Thiessen, *et al.* [13] and Mohr, Kastner, and Jahn [14] introduces opportunity charging for battery-powered vehicles. The charging strategy is to implement opportunistic charging as part of the operational cycle. This strategy assumes a sufficient number of recharging stations are strategically placed throughout the terminal to provide quick and convenient power connections. Charging equipment for a couple of minutes, with high charging power, provides enough energy for up to 0.5-2 hours of operation, depending on charging power and battery capacity. Container terminals with this design are in the concept stage, with real-life demonstration projects underway to assess technical feasibility.

According to Mohr, Kastner, and Jahn [14], the opportunity charging policy offers benefits such as easy integration of smaller batteries into vehicle design and reduced downtime for charging. A downside is the need for a large amount of charging locations, resulting in higher costs for the terminal operator.

The research by Li, Peng, Tian, *et al.* [33] complements the opportunity charging policy with the addition of partial charging. With partial charging, the device may stop charging before the battery is fully charged. With a multi-integer programming model of a fleet of 12 B-AGVs, the authors were able to test this policy against both fixed threshold charging (conservative) and full charging policies. Results showed that the combination of opportunity-interval charging and partial charging could result in lower out-of-operation time for the vehicles. Frequent charging leads to a reduced average charging time and more B-AGVs could be online to perform container transportation jobs.

The concept of the opportunity charging policy can be combined with high-capacity wireless charging. The work by Heo, Lee, Jeon, *et al.* [34] describes how inductive chargers, located at the quay and on RTGs, can be used to charge BTTs when operating in a terminal. During the operational cycle, the BTT operates as usual and is charged wireless during interchange operations. This ensures no loss in production but requires expensive, energy-hungry, chargers to be installed at every RTG and QC transfer point.

3.2.4. Pre-Emptive Charging

The work by the authors Ma, Zhou, and Stephen [32] introduces the progressive, or pre-emptive, charging policy for battery-powered container terminal equipment. Compared to the fixed threshold policy, the progressive charging policy allows equipment to be charged more frequently when an idle charger is available.

Before allocating a new job to a piece of equipment, the terminal operating system checks the SoC of all available pieces of equipment. If a piece of equipment has a SoC of less than 50% this vehicle is labelled as available to charge. The nearest three chargers are checked for availability. If a charger is available the vehicle is ordered to charge. If no chargers close by are available, the vehicle will accept a new container job. When the SoC reaches a level below 15% the vehicles can not accept any more jobs and are sent to be charged. At the charging location, all batteries are charged to full capacity. The progressive policy takes advantage of the idle status of chargers, increasing their utilisation. Furthermore, the policy may reduce the likelihood of the vehicle reaching the minimum SoC, which reduces the out-of-operation time of these vehicles.

In Table 3.1 all aforementioned charging policies, equipment types, charging methods and authors are summarised.

Charging Policy	Equipment type	Charging method	Authors
Non-operating Hours Charging	*Not specified*	Conductive	Simpson, Asce, Thiessen, *et al.* [13]
	BTT	Conductive	Mohr, Kastner, and Jahn [14]
Fixed Treshold Charging	AGV	Conductive	Sun, Zhai, Li, *et al.* [31]
	Not specified	Conductive	Simpson, Asce, Thiessen, *et al.* [13]
	AGV	Conductive	Ma, Zhou, and Stephen [32]
	BTT	Conductive	Mohr, Kastner, and Jahn [14]
Opportunity Charging	*Not specified*	*Not specified*	Simpson, Asce, Thiessen, *et al.* [13]
	BTT	Conductive	Mohr, Kastner, and Jahn [14]
	AGV	*Not specified*	Li, Peng, Tian, *et al.* [33]
	BTT	Inductive	Heo, Lee, Jeon, *et al.* [34]
Pre-Emptive Charging	AGV	Conductive	Ma, Zhou, and Stephen [32]

Table 3.1: Charging strategies presented in literature

3.3. Design alternatives

With the knowledge gathered during the literature study on the different charging strategies presented in Table 3.1 charging strategies for specifically charging BTTs were inventoried or adapted. This resulted in several design alternatives (DAs) that will be investigated. A design alternative comprises the combination of charging infrastructure type, location, and a charging policy. The different design alternatives will be modelled and tested during this research to determine the effect and possible implications of charging and operating a fleet of battery-powered terminal trucks. These design alternatives will be compared against a benchmark test where diesel-powered terminal trucks will be used, describing the current situation at an RTG terminal. Five different design alternatives for charging BTTs will be described shortly, Table 3.2 summarises the characteristics, strengths and weaknesses of the different strategies.

3.3.1. Base case: Diesel trucks

The base case for this research is the current situation at RTG terminals. Diesel-powered terminal trucks continuously transfer containers between the RTGs and the QCs. TTs are refuelled at fuelling stations during shift changes and cause no disturbance to any container transportation operations. This ensures high productivity. Although very efficient, due to environmental concerns and the rising cost of fuel the use of diesel-powered TTs in RTG terminals will have to decrease and ultimately stop.

During this research simulations with diesel-powered TTs will be carried out first to determine a benchmark for all the other design alternatives. The QC productivity reached by a fleet of diesel-powered TTs will be set as a benchmark for the battery-powered fleet to reach. The QC productivity is generally the key performance indicator for a terminal and serves as a good first comparison between the different charging strategies.

3.3.2. DA 1: Out of Operations Charging (OOP)

The first design alternative presented is Out of Operations Charging. The entire fleet of BTTs is recharged during non-operating hours at a parking or depot. All BTTs start a shift with a full battery. This strategy is only suitable for terminals that operate in shifts with sufficient downtime to recharge the fleet of BTTs. Effectively meaning it is only suitable for terminals that operate during the day and are closed overnight. Each vehicle needs a wired stationary charger, possibly with a lower charging capacity (see Table 2.2).

The benefit of this strategy is that the BTTs do not need to charge during a shift, resulting in high QC productivity. A major shortcoming of the strategy is the need to invest heavily in a substantial number of chargers to charge all vehicles simultaneously.

Figure 3.2 shows a possible layout for an RTG terminal where BTTs are charged out of operations. This could be done at an overnight parking or depot and can not influence terminal operations during a shift.

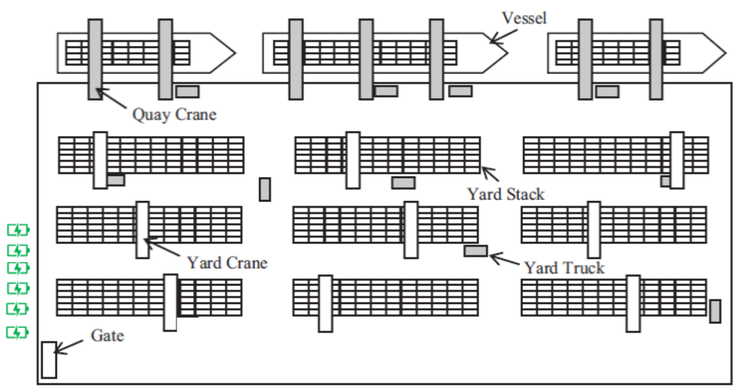


Figure 3.2: Out of Operations Charging terminal Layout

3.3.3. DA 2: Centralised Fixed Threshold Charging (CFT)

The second design alternative is based on the fixed threshold charging policy. This strategy allows BTTs to be charged during terminal operations, whilst other BTTs continue container handling. This is a necessity for RTG terminals that operate continuously. The BTTs operate until a predefined threshold value for the state of charge (SoC) is reached. When this SoC is reached, the BTT can no longer accept a new container handling job and is ordered to report to one of the available charging stations. All charging stations are located in one area in the terminal and the next available charger is assigned to the BTT requiring charging. The BTT drives to this charging station and commences charging. The battery is fully charged before the BTT is ready to accept new container handling jobs.

The benefit of this charging strategy is a relatively low investment cost compared to other strategies. Only a couple of chargers are needed to charge the full fleet of vehicles, situated at a centralised location. This ensures a single connection to the electrical grid has to be established at the terminal. A major downside to a centralised charging location is that a vehicle could have to travel a long distance to the charging location, decreasing TT availability.

Figure 3.3 shows a possible terminal layout where BTTs are charged centrally. The BTTs are charged during an operational shift and are not available to perform container operations during that time.

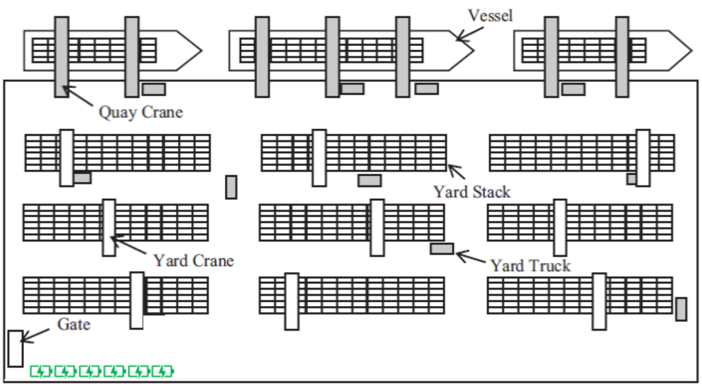


Figure 3.3: Centralised Charging terminal Layout

3.3.4. DA 3: Decentralised Fixed Threshold Charging (DFT)

Design Alternative 3 has a similar charging policy to Alternative 2 but differs in the location of the charging stations. Several charging stations are positioned at strategic locations throughout the terminal. Again the BTT can operate and accept container jobs when its SoC is not yet below the critical threshold. When a BTT requires energy replenishing an extra control step is added. For all available chargers, the driving time is calculated. The available charger that is closest to the BTT will be assigned and the vehicle is ordered to go in for a charging action. The battery is completely recharged, after which the BTT can accept a new container job. This strategy reduces the loss in production due to travel time to the charging station. A downside to this strategy is the need for several electrical grid connections throughout the terminal. This results in extra costs.

Figure 3.4 shows a possible terminal layout where BTTs are charged decentralised. The BTTs are charged during an operational shift and are not available to perform container operations during that time. A BTT is ordered to perform a charging action at the available charging stations closest to the vehicle.

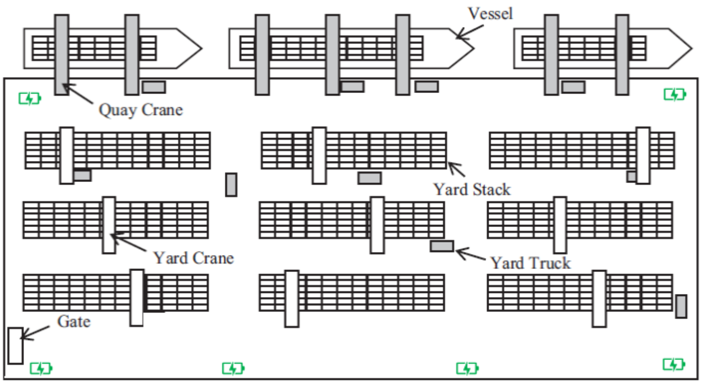


Figure 3.4: Decentralised Charging Terminal Layout

3.3.5. DA 4: Decentralised Pre-emptive Charging (DPE)

Design Alternative 4 features a terminal layout identical to Alternative 3 but introduces a distinct charging policy. Several charging stations are strategically positioned throughout the terminal. This design alternative is an adaptation of the Pre-Emptive Charging policy as described in subsection 3.2.4. The charging threshold for the fleet of BTTs is dynamic and continuously determined based on the SoC of all BTTs in the fleet.

When the average SoC of the fleet of BTTs remains above 60%, the charge threshold is set at 20%. If the average SoC falls between 60% and 50%, the charge threshold linearly increases from 20% to 40%, prompting vehicles to initiate charging earlier. Should the average SoC drop below 50%, the charge threshold is maintained at 40%.

This dynamic charging threshold ensures that more vehicles are preemptively sent for charging as the average SoC of the fleet decreases. Unlike a fixed charge threshold, which could result in multiple vehicles reaching the threshold simultaneously, the dynamic charge threshold spreads the charging. This decreases the number of vehicles charging at the same time, resulting in higher BTT availability and consequently improving terminal performance.

3.3.6. DA 5: Decentralised Opportunity Charging (DOP)

Finally, Design Alternative 5 introduces opportunity-based charging. At every RTG a wireless fast-charging charger is installed, to enable the charging of BTTs. The charging is done during the loading and unloading of containers and thus must be done with ultra-high powered chargers. The battery of the BTT is replenished enough to complete a full container cycle and return to an RTG for the next charging and container handling operation. Because BTTs are charged more often a smaller capacity battery can be used.

This strategy guarantees uninterrupted operations by ensuring that the charging power is sufficient to complete the charging process while simultaneously handling containers at the RTG. This strategy enables high availability of BTTs ensuring good QC productivity. A major downside to this strategy that cannot be overlooked is the costs. Installing a high-powered charger at every RTG results in enormous investment costs (see Table 2.2).

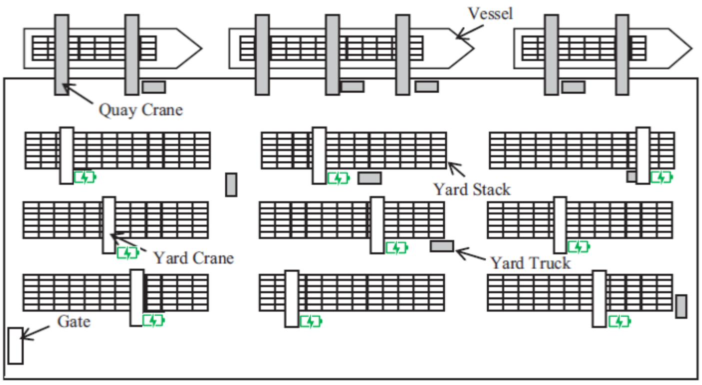


Figure 3.5: Opportunity Charging Terminal Layout

Table 3.2 provides a summary of all presented design alternatives. The performance based on investment cost and expected terminal productivity for all the different designs is given. $++$ means a low investment cost and high productivity, $--$ the opposite.

Alternative	Title	Charging infrastructure	Charge location	Charging Policy	Investment cost	Productivity
Base case	Diesel TT	-	-	-	+ +	+ +
DA1	Out of operations Charging	Wired stationary	Centralised	Non-operating hours	+ -	+ +
DA2	Centralised Fixed Threshold Charging	Wired stationary	Centralised	Fixed treshold	+ +	- -
DA3	Decentralised Fixed Threshold Charging	Wired stationary	Decentralised	Fixed treshold	+	+ -
DA4	Decentralised Pre-emptive Charging	Wired stationary	Decentralised	Pre-emptive	+	+
DA5	Decentralised Opportunity Charging	Inductive	Decentralised	Opportunity	- -	+ +

Table 3.2: Design Alternatives

3.4. Conclusion

This third chapter discussed several charging strategies. First, a literature study introduced different general charging strategies for charging battery-powered container terminal equipment. With this knowledge a variety of design alternatives for charging battery-powered terminal trucks was presented that will be tested in this research. To conclude, this chapter answered sub-questions 3 and 4.

3. *Which charging strategies are proposed in the literature?* During a literature review different charging strategies proposed in the literature were investigated. The charging strategies included a combination of four different charging policies: Non-operating hours, Fixed Threshold, Opportunity and Pre-Emptive Charging and two charging infrastructure methods: conductive or inductive.

4. *What are possible design alternatives for charging battery-powered terminal trucks?* 5 different design alternatives for charging battery-powered container terminal trucks were presented. These design alternatives are Out of Operations Charging, Fixed Threshold Centralised Charging, Fixed Threshold Decentralised Charging, Decentralised Pre-Emptive Charging and Decentralised Opportunity Charging.

4

Model

This chapter will discuss the model that describes the operation of an RTG terminal which utilises a fleet of battery-powered terminal trucks as transportation vehicles. This chapter will also answer the fifth sub-question, *How can the operation of a container terminal, including the operational profile and charging of battery-powered terminal trucks, be represented by a model?*

4.1. Model Objective

To test and compare the performance of the different charging strategies introduced in section 3.3 a model needs to be developed that represents the operation of an RTG terminal, the operational profile of battery-powered terminal trucks and the charging of these trucks. The main objective of the model is to test and compare the different design alternatives. With the use of different (K)PIs, the performance of each alternative is compared to a base case diesel-powered set-up and also compared to one another. Figure 4.1 gives a simplified representation of the model, the different components needed for the model will be discussed shortly.

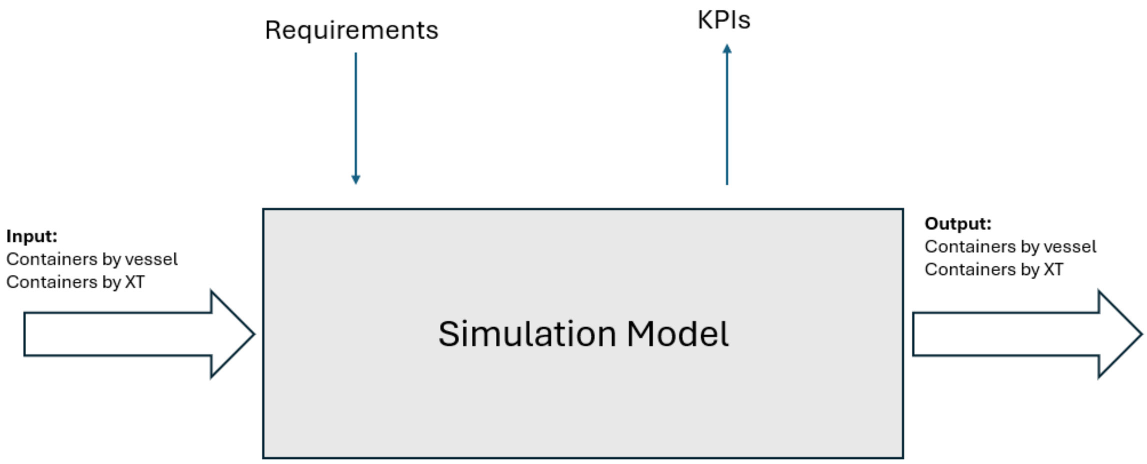


Figure 4.1: Black box representation of the model

4.2. Model Input and Output

The model will use inputs that are generated at both ”ends” of the model. These will be containers that arrive at the gate via XTs and containers that need to be unloaded from the vessels at the quay. These containers need to be handled by the QCs, RTGs and BTTs in the simulation model. The containers will leave the model via the loading of vessels and XTs leaving the terminal at the gate. The generation of containers at the gate is distributed according to an arrival pattern. Containers generated at the QC follow a fixed load plan which will be explained later.

4.3. Performance Indicators

Several (K)PIs will be used to illustrate and document the performance of the different design strategies. The model logs these values which ultimately are used to produce graphs and tables to quantify the performance. The (K)PIs used are itemised below. Some additional indicators are also given. These add insight into the performance of different strategies but are of less importance to the overall comparison of strategies. Furthermore, the costs of the different strategies can be calculated with the use of (K)PIs produced by the model, but does not follow directly from the model.

Key Performance Indicator:

- QC productivity per hour

Additional performance indicators:

- Status of (B)TTs
- (B)TT productivity per hour
- Energy consumption BTTs per hour and box moved
- SoC of BTTs over time
- Utilisation of charge lanes for each hour

4.4. Requirements

The model needs to meet several requirements regarding the proper representation of an RTG/BTT terminal

- The model must be able to produce the (K)PIs of section 4.3
- The model must accurately simulate the consumption of energy by the BTTs
- The model must include the charging of BTTs
- It must be able to implement different charging policies and charging infrastructures
- It must be able to change the layout of the terminal regarding charge lane location
- It must capture the operations of the QCs, RTGs and BTTs (driving, handling, queueing etc.)

4.5. Assumptions

Some assumptions are needed to ensure a stable and quick simulation.

- Only standard 20 and 40-foot containers are considered.
- Only single and twin lifts are considered for quay crane lifting operations.
- BTTs consume energy during accelerating, driving and stationary. They reproduce energy during braking.
- The charging curve for replenishing the battery of the BTT is regarded as linear.
- The driving characteristics for battery and diesel-powered terminal trucks is the same.

4.6. Model Description

The models used in this research will be built in the simulation software TIMESQUARE, developed by Portwise. This model already meets many of the requirements set in section 4.4, although some functions need to be added. The RTG/TT model used by Portwise will serve as the basis for a model including battery-powered terminal trucks and the charging of these vehicles. The model is a general representation of RTG terminals and its most common components. It is not a true representation of an existing terminal but has been built during years of development and testing of different RTG terminals. It is a well-tested and validated model that Portwise uses for numerous projects.

4.6.1. RTG terminal model

Figure 4.2 shows a figure of an example RTG/TT model. The model shows a typical representation of an RTG terminal with many RTGs (orange, grey and green squares) handling the containers in multiple yard modules. RTGs can move between the different modules when needed. Active RTGs are green and non-active RTGs are grey, an RTG switching modules RTG is orange. Several QCs, depicted at the bottom of the figure, handle the different vessels docked at the quay and move containers between the BTTs and the vessels. XTs delivering or picking up containers pass through the gate, situated here in the upper left corner. After an XT arrives through the gate it drives over the blue driving lanes until it arrives at the correct RTG, where a container transfer is made. XTs exit the model again via the same gate. TTs use the same driving lanes as XTs and shuttle containers between the quay and the yard. The colour of the cabin distinguishes the two types of vehicles. The XT has a blue cabin, whereas the TT has a red cabin.

Figure 4.2: RTG terminal model in Timesquare

4.6.2. Operations

The terminal operations simulated are controlled by a central Terminal Operating System (TOS). The TOS manages the loading and unloading plan of the vessels and controls which (B)TT, RTG and QC handles which container. It matches container handling orders to the different equipment. Each vehicle has individual integrated controls to simulate the driving and route handling. Finally, the TOS also manages the charging orders for the BTTs. Following the implemented charging policy, it determines when BTTs can no longer accept container operations and are ordered to charge.

4.7. Battery-powered terminal truck

For this research, the RTG/TT model produced by Portwise must be modified to enable the implementation of battery-powered terminal trucks. This will need to contain both the operating profile (driving, accelerating, cornering, etc.), electrical energy consumption and charging locations.

4.7.1. Operational profile

Within the Portwise RTG model, the TTs are simulated and animated using a set of general parameters. The driving, braking, accelerating or standing still is simulated for every timestep. This is done for each BTT and statistics about the different driving states are logged. Adapting this to work for BTTs is quite simple. The general parameters used for the BTTs in this research are given in Table 4.1. These parameters describe the different speeds and lengths set for all BTTs and will not change for different charging strategies.

Parameter	**Value**	**Unit**
Max. straight speed	8.4	m/s
Max. Curve speed	4.2	m/s
Acceleration No load	0.5	m/s^2
Accelration Loaded	0.3	m/s^2
Deceleration No load	0.6	m/s^2
Deceleration Loaded	0.4	m/s^2
Turning radius	6	m
Length (including trailer)	19	m
Width	3	m

Table 4.1: General parameters BTT

4.7.2. Energy consumption BTT

One key functionality that needs to be added to the model is the energy consumption by BTTs. This will simulate the BTTs using electrical energy from their batteries and keep track of the SoC of the vehicles. The power required to operate the electrical motors in the BTTs differs during different driving states. As shown in the table, a BTT requires alot of power during acceleration whilst fully loaded and only uses a small amount of energy during a standstill. During the simulation at every timestep, the current power usage of the BTTs is determined and used to calculate the energy consumption during that timestep. Table 4.2a gives the range of engine power depending on different speeds and loads during acceleration and constant driving. The current power usage is calculated by linear interpolation for the current load and speed. At 0 m/s the BTTs are not driving but still use a small amount of energy to keep systems up and running. During braking some energy can be regenerated resulting in some recuperated energy. The power curve for this is given in Table 4.2b. With the power usage for a given timestep, the energy consumption of the BTT is calculated and the SoC of the individual BTTs is updated.

The engine power parameters have been determined with the use of publicly available BTT characteristics (see Table 2.1). These values are set for all charging strategies and implemented in the model.

Speed(m/s) \ Load(t)	0	30
0	1 kW	1 kW
8.4	150 kW	300 kW

(a) Acceleration and constant driving

Speed(m/s) \ Load(t)	0	30
0	1 kW	1 kW
8.4	-30 kW	-60 kW

(b) Deceleration

Table 4.2: Engine Power tables

4.7.3. Charging Stations

When the battery of the BTT needs to be recharged, this is done at a charging station. Charging is done either conductive or inductive. A charging station can house multiple charging lanes where BTTs can be charged. At a charging station the BTTs park for a certain amount of time whilst their battery is replenished. Charging is done linearly to a set amount of SoC. The charging time depends on the battery capacity of the vehicle and the charging capacity of the charging stations. These capacities are determined by charging strategy choices and differ between the different design alternatives. Whilst a BTT is charging its SoC is updated every timestep and logged.

Portwise had some functionalities of charging stations in some of its models. These were only used for battery-swapping AGVs and thus needed to be adapted to work with BTTs. The ability to charge via conductive or inductive charging was implemented.

4.8. Charging strategies

The different charging strategies need to be implemented in the RTG/BTT model. Each charging strategy consists of a charging infrastructure and charging policy. Both are easily adaptable in the model for a given test. Furthermore, the number of BTTs, the battery capacity of the fleet, charging power and the number of available charge lanes are also adaptable. Every design alternative utilises a different specific control structure implemented in the TOS. These will be described shortly for all alternatives. After each reported completed order, the control loop is initiated by the TOS to determine which BTTs have to charge and which are available to transport containers.

4.8.1. DA1: Out-of-Operations Charging (OOP)

The first design alternative uses a substantial number of wired chargers to charge the BTTs during downtime at the terminal, often at night. At the start of the simulation, all vehicles have a maximum SoC and will not need intermediate charging. The battery capacity of the BTTs is enough to complete a full 8-hour shift. The SoC of each BTT is still monitored.

Figure 4.3 describes the control loop as performed by the TOS during operations. When the plan cycle is initiated it first checks which vehicle is available next from a list of all vehicles. A vehicle is only available if it currently not charging or not performing a container order. BTTs are assigned to perform container orders until the battery level reaches a critical SoC. For this charging strategy, this should never occur, but it is still included as a precaution. If a BTT were to accidentally it is ordered to return to the depot and park there. It is no longer available to perform container orders.

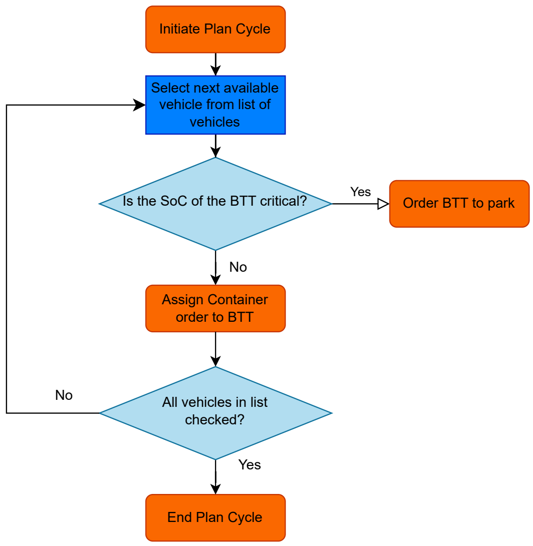


Figure 4.3: Control structure DA1

4.8.2. DA2: Centralised fixed threshold Charging (CFT)

The second design alternative uses several centrally located charging stations with several charging lanes per station to charge the BTTs during container terminal operations.

Figure 4.4 shows the control structure as used by the TOS for this design alternative. When a BTT reaches a fixed charging threshold it is no longer allowed to transport containers and is ordered to go in for a charge after finishing its current job. The availability of the charging lanes is checked. If a charging lane is available at any of the charging stations the BTT is ordered to charge at that lane. If no lanes are available the BTTs are ordered to park near the charge stations. Once a charge lane becomes available it will be ordered to go in for a charge.

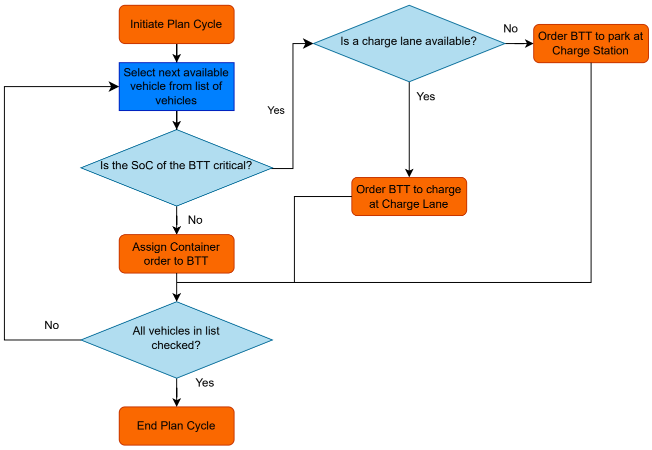


Figure 4.4: Control structure DA2

4.8.3. DA3: Decentralised fixed threshold Charging (DFT)

The third design alternative utilised charging stations spread throughout the terminal at strategic locations.

Figure 4.5 shows the control structure as used by the TOS for this design alternative. When a BTT reaches a fixed charging threshold after finishing its current order, it is no longer allowed to transport containers and is ordered to go in for a charge. The availability of the different charging lanes is checked. If more than one charge lane is available the closest charge lane, based on driving time, to the BTT is selected. If no charge lanes are available the BTT is ordered to park near the charge station where the next available charge lane is situated. When the charge lane becomes available the BTT is ordered to go charge.

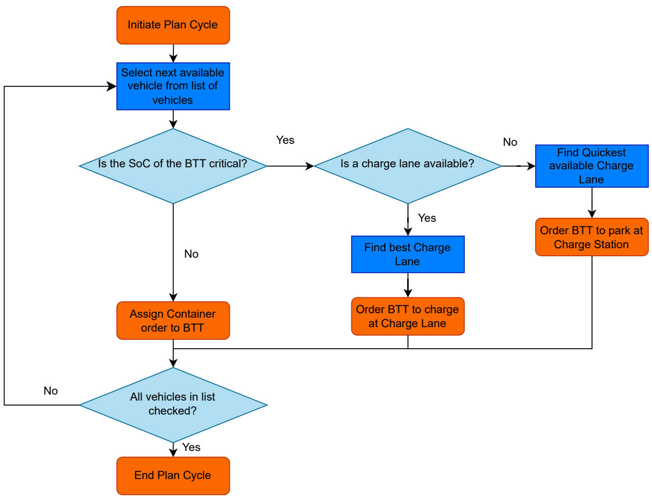


Figure 4.5: Control structure DA3

4.8.4. DA 4: Decentralised Pre-emptive Charging (DPE)

The fourth design alternative uses the same charging infrastructure as the previous charging strategy.

Figure 4.6 describes the control structure used by the TOS for this charging strategy. For all available BTTs, the SoC is checked. If it is critical, below 20%, it is ordered to go charge or park at a charge station as before. Next, the average SoC of the fleet of BTTs is determined and the dynamic charge threshold is calculated. When the average SoC is above 60%, the charge threshold is set at 20%. If the average SoC falls between 60% and 50%, the charge threshold linearly increases from 20% to 40%, prompting vehicles to start charging earlier. If the average SoC drops below 50%, the charge threshold is fixed at 40%. If the SoC of the BTTs is below the charge threshold, the availability of the charge lanes is checked. If more than one charge lane is available, the charge lane closest, based on driving time, to the BTT is selected. If no charge lanes are available the BTT continues to perform container orders.

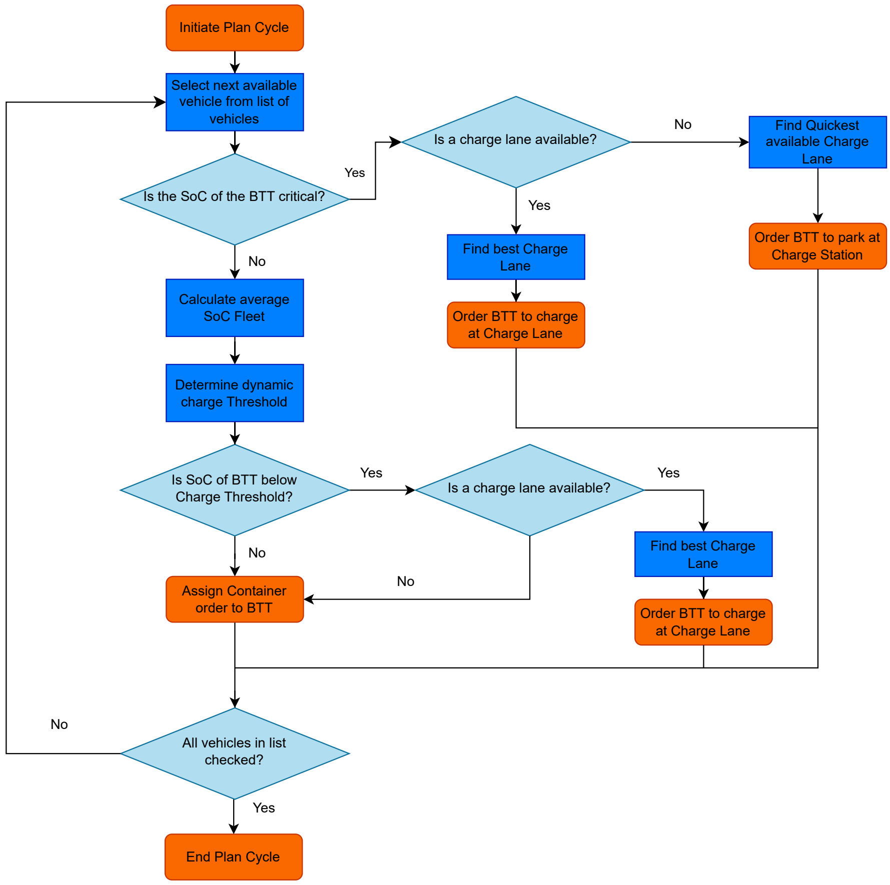


Figure 4.6: Control structure DA4

4.8.5. DA 5: Decentralised Opportunity Charging (DOP)

The last design alternative uses high-powered inductive chargers at every RTG to charge the BTTs during the period it is alongside the RTG. This will ensure that no time is lost during container operations. The model simulates this by updating the SoC of the BTT by a certain amount every time it completes a transfer with an RTG (both pick-up and delivery). This amount is the average energy consumption per container moved in the terminal. This needs to be determined with a preliminary simulation. In this research, the average energy consumption per container measured during the testing of design alternative 1 will be used. To make sure no BTT depletes its battery too much, the SoC of all BTTs is still monitored. The TOS uses the same control structure as presented in Figure 4.3.

4.9. Verification and validation

Verification of the model is a crucial step in the modelling process. It ensures that the model is implemented according to the specifications. The RTG/TT model that serves as the base for the models developed during this research, has been employed by Portwise for several years. It has been developed to represent a simulation of real-life RTG terminal operations. During its implementation in many projects the validity has been established by comparing it to data provided by terminal operators.

The BTT and Charging strategies models created for this thesis were verified using code reviews and tracing methods, and was further assessed by examining the animations generated by the simulation software, in line with the approach described by Sargent [35].

Given the limited adoption of BTTs in container terminals, it was not possible to validate the models using real-world data. Instead, industry experts from Portwise reviewed the models and confirmed that they were representative of real-world conditions. QC productivity and BTT operating status were checked against experiments with diesel-powered TTs.

4.10. Conclusion

This fourth chapter discussed the model used during this research. First, the model objective, the model input and out, KPIs, requirements and assumptions were discussed. After this, a description of the RTG/TT model developed by Portwise was introduced. This model has been adopted to work with BTTs and the different charging strategies proposed in this research. This chapter answered the fifth sub-question

5. *How can the operation of a container terminal, including the operational profile and charging of battery-powered terminal trucks, be represented by a model?* The model representing the battery-powered BTT operation in an RTG terminal includes the energy consumption during driving, regenerative braking and accelerating and updates the SoC of the BTT accordingly for every timestep. Furthermore, it includes different charging infrastructures comprising of wired or inductive charging methods. Combined with implementing different charging policy rules this results in a model representing charging strategies that simulate operations and charging of BTTs.

5

Experimental Plan

This chapter describes the experimental plan that was carried out in combination with the simulation model to test the performance of the different charging strategies. First, the configuration of the RTG terminal is described. After this, a benchmark test using diesel TTs is described. Finally, the different experiments to test the five design alternatives will be presented.

This chapter sets out to answer sub-question 6: *How can the different charging strategies be implemented and tested in a terminal operation simulation model?*.

5.1. Test Scenario

Throughout all experiments the test scenario involves a peak-load situation at the terminal, with containers being simultaneously discharged and loaded onto three moored vessels, representing the terminal's maximum berth capacity. Consequently, all available QCs are in operation, and all (B)TTs are active, ensuring a constant flow of jobs for the horizontal transport vehicles. Additionally, 150 road trucks will arrive each hour through the gate, either delivering or picking up containers at the terminal.

5.2. Terminal Configuration

During all tests the general configuration of the RTG terminal and the (B)TTs is fixed. Table 5.1 gives some dimensions and number of equipment used in the simulation model. These values are provided by Portwise and do not correspond to a specific RTG terminal. As described in the last section the terminal operates at full capacity during all simulations, and the maximum number of cranes are used.

Parameter	Value	Unit
Number of Storage yard blocks	32	-
Number of RTGs	32	-
Number of QCs	10	-
Quay Length	1200	m
Terminal Depth	300	m
Number of Vessels	3	-
External Trucks per hour	150	-
Containers throughput per year	900.00	-

Table 5.1: Terminal configuration parameters

The driving and size parameters of all diesel TTs and battery-powered ones are the same. These and other general parameters are given in Table 5.2

Parameter	Value	Unit
Max. straight speed	8.4	m/s
Max. Curve speed	4.2	m/s
Acceleration No load	0.5	m/s^2
Accelration Loaded	0.3	m/s^2
Deceleration No load	0.6	m/s^2
Deceleration Loaded	0.4	m/s^2
Turning radius	6	m
Length (including trailer)	19	m
Width	3	m

Table 5.2: General parameters (B)TT

The different BTT engine power settings used as the default BTT setting in all experiments is given in Table 5.3

Speed(m/s) \ Load(t)	0	30
0	1 kW	1 kW
8.4	150 kW	300 kW

(a) Acceleration and constant driving

Speed(m/s) \ Load(t)	0	30
0	1 kW	1 kW
8.4	-30 kW	-60 kW

(b) Deceleration

Table 5.3: BTT engine power settings

5.3. KPIs

Two key performance indicators (KPIs) will be used to evaluate and compare the proposed charging strategies with the current diesel-powered operations, as well as to assess the effectiveness of different charging strategies. The primary KPI, QC productivity, will be assessed through simulation experiments. The second KPI, costs per strategy, will be calculated based on the productivity of QC and (B)TT, as determined during these simulations.

5.3.1. QC productivity

To test the performance of the different charging strategies the KPI of QC productivity is used. This number indicates the average number of containers moved per QC per hour. It is often the most important performance indicator for a terminal and critical to ensure that a strategy can perform at a required performance level.

5.3.2. Costs

To quantitatively compare the cost of the different charging strategies some cost estimations concerning vehicles, charging infrastructure and operational costs have been made using publicly available sources and expert knowledge by Portwise employees [25] [36].

Table 5.4 and Table 5.5 give some cost estimations for the different equipment types, charging infrastructure and operational costs.

Operational cost estimations are made for the entire lifetime of the fleet of (B)TTs set at 10 years. The operating cost of the fleet of BTTs for each strategy is calculated with the estimated operational hours per year, calculated with the average peak QC productivity and average (B)TT productivity both acquired from the simulations performed and the total container throughput of the RTG terminal per year (see Table 5.1). The productivity estimations obtained from the simulation are based on performance during peak operational periods. To provide an accurate cost estimate for the total operational life of the (B)TT, Portwise assumes that the terminal operates at full capacity for 80% of the time, which will be used during this research.

Equipment/Charging Infrastructure	Cost
Diesel Terminal Truck	€ 120,000.00
Battery-Powered Terminal Truck (25 kW)	€ 190,000.00
Battery-Powered Terminal Truck (150 kW)	€ 250,000.00
Battery-Powered Terminal Truck (350 kW)	€ 350,000.00
Charger 50 kW	€ 45,000.00
Charger 150 kW	€ 90,000.00
Charger 500 kW	€ 500,000.00

Table 5.4: Cost estimations Equipment and Charging infrastructure

Operating cost per operational hour		
	Diesel	Battery
Energy consumption	10 l/h	20 kWh/h
Fuel/Energy price	€1.60/l	€0.20/kWh
Maintenance cost per operating hour	€ 13.60	€ 9.50
Total operating cost per operating hour	**€ 29.60**	**€ 13.50**

Table 5.5: Cost estimation Operational Cost

5.3.3. Extra Performance Indicators

Additional performance indicators will be utilised to provide insights into the effects of various strategies on terminal performance. These additional performance indicators will also be displayed in graphs and tables when appropriate.

- (B)TT status
- State-of-Charge BTTs over time
- Energy Consumption
- Charger Utilisation per hour

The first of these is the status of the (B)TTs, which shows what percentage of the time the vehicle is occupied with a certain task type. The second is the state-of-charge or SoC of each BTT in the fleet. This gives an insight into the battery status of the different vehicles during the shift. Complementary to this is the energy consumption of the BTTs, calculated as the average energy consumption per hour per BTT and average energy consumption per box moved. Finally, the charger utilisation per hour depicts the average number of charging lanes occupied per hour.

5.4. Experimental comparison Charging Strategies

To assess the performance of different charging strategies, the simulation model developed during this research will be employed. Experiments will be conducted to test various configurations of the proposed charging strategies. Additionally, the performance of these strategies will be compared to that of a terminal using diesel-powered terminal trucks. The results from the diesel-powered terminal will serve as a benchmark for evaluating the relative performance of the charging strategies. All experiments are summarised in Table 5.6.

5.4.1. Benchmark: Diesel TT

In the benchmark experiments (Experiments 1, 2, and 3), varying numbers of diesel-powered terminal trucks will be used to assess the impact and performance of the RTG terminal, establishing a reference point for subsequent tests and comparisons. The first experiment utilises a fleet of 40 TTs, increasing by 10 TTs in the following two experiments. Neither charging nor refuelling is included in the simulation.

Figure 5.1 gives an overview of the model used in the Timesquare software.

Figure 5.1: RTG terminal model Benchmark and DA1

5.4.2. DA1: Out of Operations Charging (OOP)

Experiment 4 will evaluate the effectiveness of implementing an out of operations (OOP) charging strategy for a fleet of battery-powered terminal trucks. These BTTs are charged at a centralised charging station during downtime at the terminal. As the RTG model used in Timesquare only simulates container operations during active terminal hours, the actual charging of the BTTs is not included in the simulation. All BTTs enter the simulation with a fully charged battery, and their state of charge (SoC) is monitored throughout operations. Since charging does not impact container handling, a medium-sized fleet of 50 BTTs has been selected for this experiment. To ensure the BTTs can complete a full 8-hour shift, a battery size of 350 kW, the largest available from manufacturers (Table 2.1), has been chosen. Given the extended downtime, a minimal charging capacity of 50 kW per charger is sufficient. Each BTT requires a charger, resulting in the need for 50 chargers. This experiment will also investigate the average power consumption per hour and container moved. These results will be used during the testing of the opportunity charging policy of DA5.

Experiment 4 utilises the same RTG model as the benchmark (Figure 5.1) but with different settings. The TTs are now electric and power consumption is logged. As mentioned with Table 5.2 the driving and geometry parameters of BTTs and TTs are identical in the model.

5.4.3. DA2: Centralised Fixed Threshold Charging (CFT)

To test the performance of the Centralised Fixed Threshold charging strategy experiments 5,6,7 and 8 will be conducted. These experiments are the first where the consequences of charging during container handling operations are investigated. Due to the necessity to charge during a shift extra vehicles are added to the fleet of BTTs. 60 BTTs are utilised during these experiments with a battery capacity of 150 kWh and are charged at centrally located charging lanes. The number of charge lanes installed increases with consecutive experiments. The charging policy implemented is that of a fixed threshold. The threshold is set at 20%.

Figure 5.2 shows the RTG model used for the experiments. Charging is done at one of the charging stations at the top left corner. If no charge lane is available the BTT is ordered to park at the adjacent parking until a charging lane becomes available.

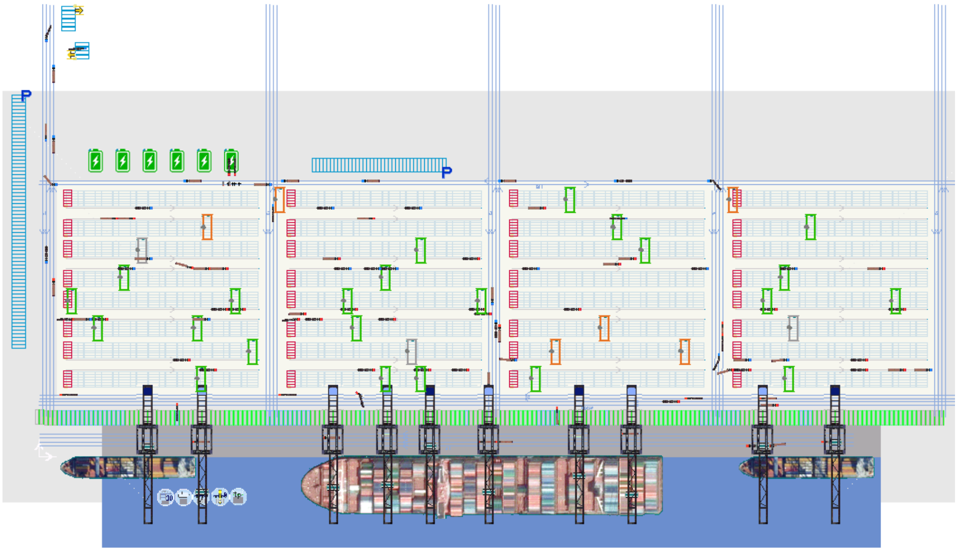


Figure 5.2: RTG terminal model DA2

5.4.4. DA3: Decentralised fixed threshold Charging (DFT)

To test the effect of charge station location Experiments 9 to 12 will be conducted. The same fleet of BTTs and chargers as DA2 is used, only the locations of the charge lanes are different.

Figure 5.3 provides an overview of the model used in these experiments. Six charging stations are positioned throughout the terminal. These will house a varying number of available charging lanes between the different experiments. If no charging lanes are available during the simulation the BTTs are ordered to park at a parking at the next available charger.

5.4.5. DA4: Decentralised Pre-Emptive Charging (DPE)

Subsequently, Experiments 13 to 16 are conducted to assess the effects of pre-emptive charging. The fleet of BTTs, as well as the chargers and their locations, remain identical to those used in the DA3 experiments. However, the charging policy is adapted to incorporate a dynamic charge threshold, as outlined in the previous chapter. As before, the number of available charging lanes is increased with each successive experiment.

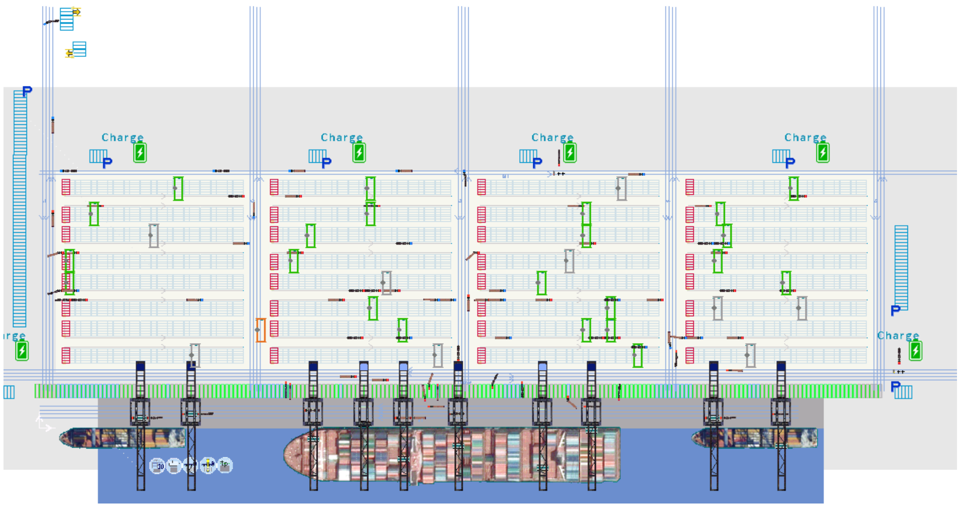


Figure 5.3: RTG model DA3 and DA4

5.4.6. DA5: Decentralised Opportunity Charging (DOP)

Finally, Experiment 17 concludes the testing and is used to investigate Opportunity Charging at the RTGs. Each of the 32 RTG is equipped with a high-capacity charger of 500 kW. These chargers replenish the battery of the BTTs every time one visits an RTG. The amount of charge that is added is adapted from the average power consumption per box moved which will be calculated during Experiment 4. Because the BTTs are charged during container handling operation a smaller fleet of 50 BTTs is selected. Because the BTT is charged more frequently during the shift it can operate with a smaller battery capacity.

Figure 5.4 shows the model used for the RTG terminal in Experiment 17. Because the chargers are installed at the RTG there is no visual cue in the model representation.

Figure 5.4: RTG terminal model DA5

Table 5.6 summarises the before-mentioned experiments and provides an overview of the different test configurations.

Experiment	Design Alternative	Number of (B)TT	Charge Location	Charging Policy	Battery Capacity (kWh)	Charging Capacity (kW)	Number of Charge Lanes
1	Diesel	40	-	-	-	-	-
2		50	-	-	-	-	-
3		60	-	-	-	-	-
4	OOP	50	Depot	Out of Operations	350	50	50
5	CFT	60	Centralised	Fixed threshold	150	150	10
6		60	Centralised	Fixed Threshold	150	150	12
7		60	Centralised	Fixed Threshold	150	150	14
8		60	Centralised	Fixed Threshold	150	150	16
9	DFT	60	Decentralised	Fixed Threshold	150	150	10
10		60	Decentralised	Fixed Threshold	150	150	12
11		60	Decentralised	Fixed Threshold	150	150	14
12		60	Decentralised	Fixed Threshold	150	150	16
13	DPE	60	Decentralised	Pre-Emptive	150	150	10
14		60	Decentralised	Pre-Emptive	150	150	12
15		60	Decentralised	Pre-Emptive	150	150	14
16		60	Decentralised	Pre-Emptive	150	150	16
17	DOP	50	Decentralised	Opportunity	25	500	32

Table 5.6: Experiment configurations

5.5. Replications and Run-Length

5.5.1. Fixed load plan

To evaluate the various charging strategy configurations, several simulations are required. A load plan is used to determine which containers can be handled by the QCs and BTTs. The load plan is divided into 25 sections, resulting in 25 replications per experiment. The fixed load plan is applied consistently across all experiments. This ensures that the QCs are presented with the same mix and type of containers in each test configuration. While the QCs are exposed to the same possibilities within the load plan, they may not handle the same containers in every replication. Each replication executes a portion of the load plan within a single simulation run. Furthermore, each specific replication within any experiment starts at the same point in the load plan. For example, replication 4 in experiment 3 will use the same part of the load plan as replication 4 in experiments 5, 6, 7, and so on.

5.5.2. Run-length

Each run lasts for 8 in-simulation hours, with the initial hour allocated as a start-up period where no data is recorded. Consequently, the effective duration for each experiment is 7 in-simulation hours.

5.5.3. Failed simulation replications

Not all simulations will succeed on the first try, as some may fail at a certain point. The reasons for these failed runs are processes handled by parts of the Portwise simulation model not involving a charging strategy. The Portwise model simulates the interaction of all vehicles in the terminal. For this, it uses mathematical distributions and random numbers to set parameters. Examples of these are the arrival pattern of trucks at the gate, the handling times of RTGs and QCs and the sequence of containers being picked up from the RTG. These interactions could lead to unrealistic congestion at the terminal or discrepancies in operations, ultimately preventing QCs from functioning properly. This issue is a simulation artefact and does not accurately reflect the real-life operation of an RTG terminal, so it needs to be addressed. To mitigate these external effects, failed runs not caused by the charging strategies are filtered out.

To filter out these failed runs, the following criterion is applied: if the productivity of one or more QCs drops to zero at any point and remains so until the end of the run, that run is considered unsuccessful.

These replications will be re-run until each configuration completes a simulation run of each part of the fixed load plan. Re-running a simulation uses different distributions and random numbers for the interactions as stated, but the same battery charging parameters and control structures.

5.6. Conclusion

In conclusion, this chapter has provided an answer to sub-question 6: *How can different charging strategies be implemented and tested in a large-scale terminal operation simulation model?* By applying specific terminal configuration settings and incorporating BTT driving and power consumption parameters, the experiments are designed to evaluate the practical implementation and performance of various charging strategies within an RTG terminal operation simulation.

Key performance indicators (KPIs), QC productivity and cost, and additional performance metrics can assess the effectiveness of each strategy. This approach allows for a detailed comparison of strategies, considering variables such as charger locations, charging policies, charging capacities, and the number of available charging lanes.

6 Results

The results of the experiments described in the last chapter will be discussed in this chapter. With the use of these results, the final two sub-questions of this research will be answered, 7:*How do the different charging strategies, both in configuration and operation, perform?* and 8: *How do the productivity and cost of different charging strategies compare to diesel-powered RTG terminals?*

6.1. Test Results

The test results of the different experiments performed in this research will be discussed shortly. For the results of the QC productivity, the average for each experiment is used to show the performance of the different strategies. A Student's t-distribution with a significance level of 95% was used to calculate a confidence interval. All results of the replications per experiment can be found in Table B.1.

Furthermore, cost estimations of the different configurations as presented in Table 5.6 are calculated. These cost estimations are made for the entire lifetime of the fleet of (B)TTs set at 10 years. The operating cost of the fleet of BTTs for each strategy is calculated with the estimated operational hours per year, calculated with the average peak QC productivity and total volume of containers expected to move through the RTG terminal per year. With the terminal parameters as presented in Table 5.1, the expected throughput was estimated by Portwise employees to be 900,000 containers per year.

When relevant, additional performance indicators are also given.

6.1.1. Benchmark: Diesel TT

During the benchmark experiments (Experiments 1,2 and 3), a varying number of diesel-powered terminal trucks were implemented to test the QC performance of the RTG terminal configuration as used in this research. It describes the current situation at many RTG terminals and its performance establishes a reference point for the subsequent tests and comparisons.

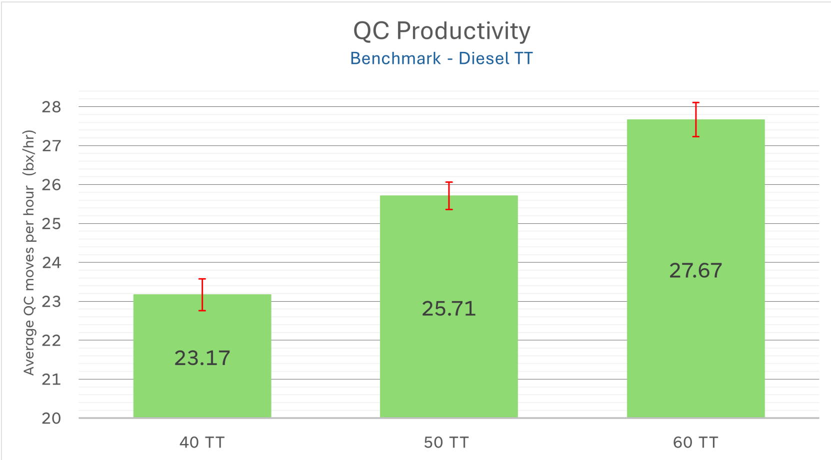


Figure 6.1: QC productivity Benchmark - Diesel TT

Figure 6.1 and Table 6.1 show the QC productivity of the diesel TT configurations. With an increasing fleet size the average QC productivity of the terminal increases with the fleet of 60 TTs performing best. The performance of the 50 TTs has been set as the minimal performance target for the subsequent configurations.

QC productivity (box/hr)			
Diesel	**40 TT**	**50 TT**	**60 TT**
Average	23.17	25.71	27.67
95% Confidence	$\pm$ 0.41	$\pm$ 0.35	$\pm$ 0.44

Table 6.1: QC productivity Benchmark - Diesel TT

Figure 6.2 gives a cost estimation of the benchmark diesel TT configurations. Although the investment costs of the BTTs are relatively low, the operating cost during the lifetime of the TTs results in significant total costs. The use of diesel as a fuel comes at a premium and the maintenance costs are also substantial (see Table 5.5). With an increasing fleet size both the investment and operational costs rise.

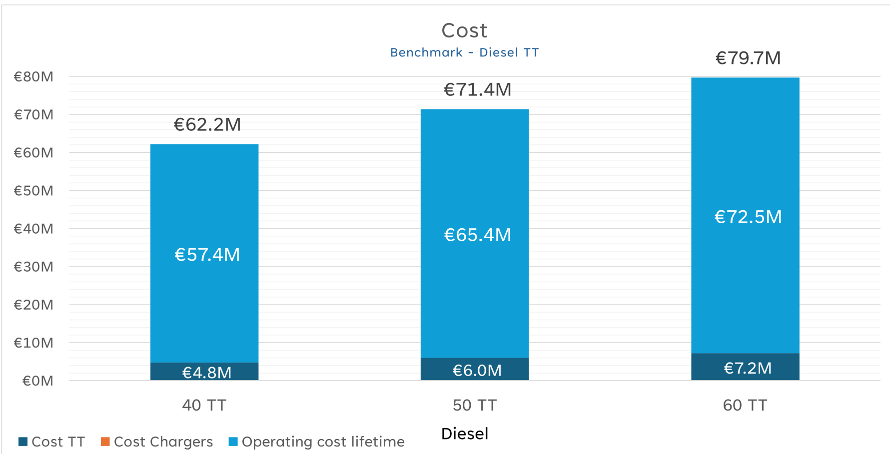


Figure 6.2: Cost estimation Benchmark - Diesel TT

6.1.2. DA1: Out of Operations Charging (OOP)

Experiment 4 tested the performance of the Out of Operations Charging strategy for a fleet of 50 BTTs. This experiment also investigated the average power consumption of the BTTs per container moved. This result has been used during the testing of the Opportunity charging policy of DA5.

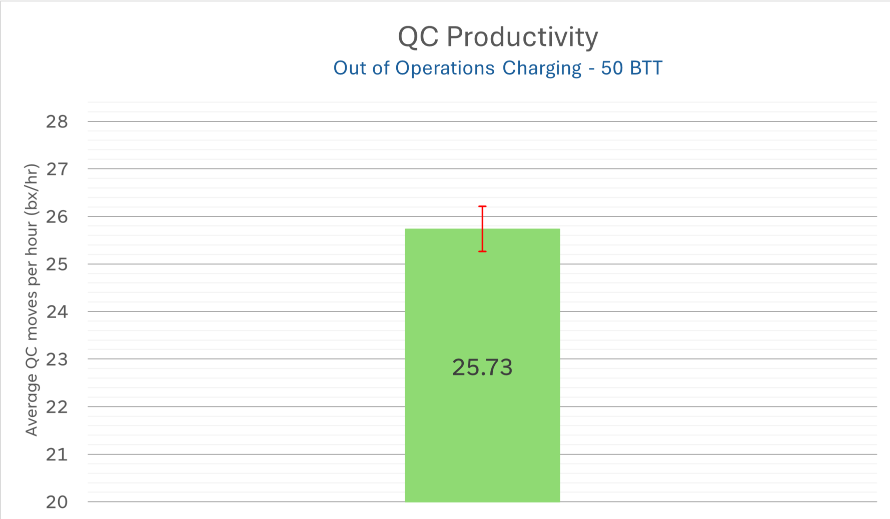


Figure 6.3: QC productivity Out of Operations Charging

Figure 6.3 and Table 6.2 show the QC productivity of the Out of Operations Charging strategy. Because charging of the 50 BTTs is done before the start of the shift it does not affect container handling operations. Due to this, the performance of this strategy is similar to that of the 50 diesel TTs as presented in the benchmark tests.

QC productivity (box/hr)	
Out of Operations Charging	
Average	25.73
95% Confidence	$\pm$ 0.48

Table 6.2: QC productivity Out of Operations Charging

Figure 6.4 provides the cost estimation for the total cost of the Out of Operations charging strategy. The investment cost of 50 BTTs and 50 low-capacity chargers amount to a significant amount. Again most of the cost comes from operational costs, although it is only about half compared to that of the diesel-powered alternatives.

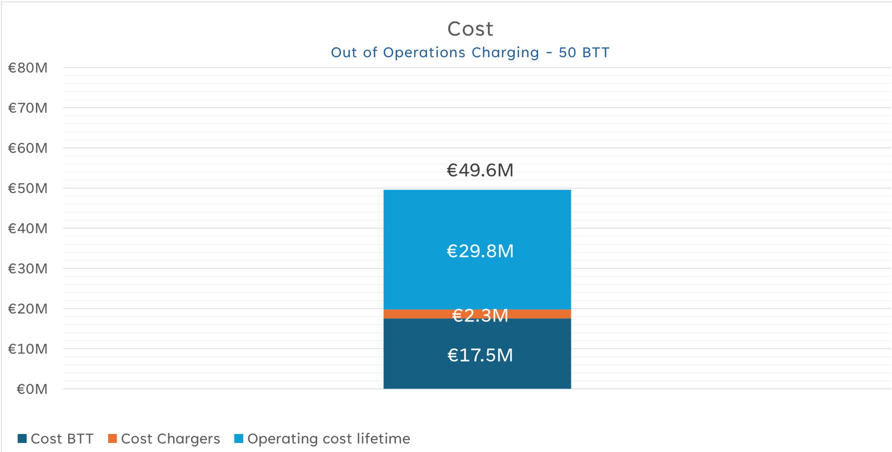


Figure 6.4: Cost estimation Out of Operations Charging

Figure 6.5 shows the average power consumption per box by BTTs. The total energy consumption is made up of several components each contributing differently. Most energy is consumed during acceleration with it accounting for over 30%. During constant driving energy consumption is lower but still significant. Hardly any energy is consumed whilst the BTT is stationary. Some energy is recuperated during braking resulting in a negative energy consumption. Consequently, the net energy consumed per box moved is 4.6 kWh. This value will be used as the amount that the battery of the BTTs is replenished during opportunity charging in the test of DA5.

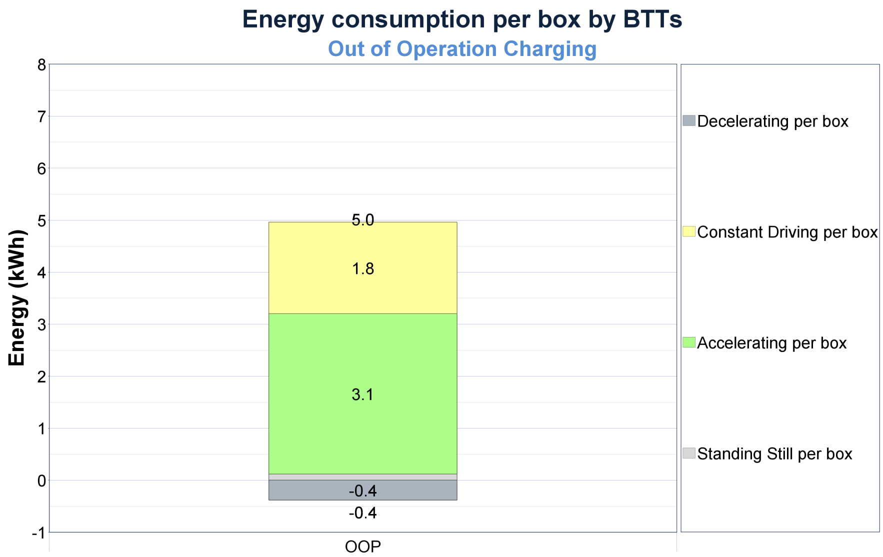


Figure 6.5: Energy Consumption per Box Out of Operations Charging

6.1.3. DA2: Centralised Fixed Threshold Charging (CFT)

To test the performance of the Centralised Fixed Threshold charging strategy experiments 5,6,7 and 8 were conducted. These experiments are the first where the consequences of charging during container handling operations are investigated. Due to the necessity to charge during a shift extra vehicles were added to the fleet of BTTs, with a total of 60 BTTs.

Figure 6.6 and Table 6.3 show the QC performance for Decentralised Fixed Threshold Charging with varying number of available charge lanes. The difference in QC productivity between the different configurations is relatively small. The only statistical QC productivity increase is between the strategy with 10 and 14 or 16 charge lanes available. Furthermore, it is noticeable that the configuration with a large number of available charge lanes, 16, is the only one with an average QC productivity close to the benchmark of 50 diesel TTs.

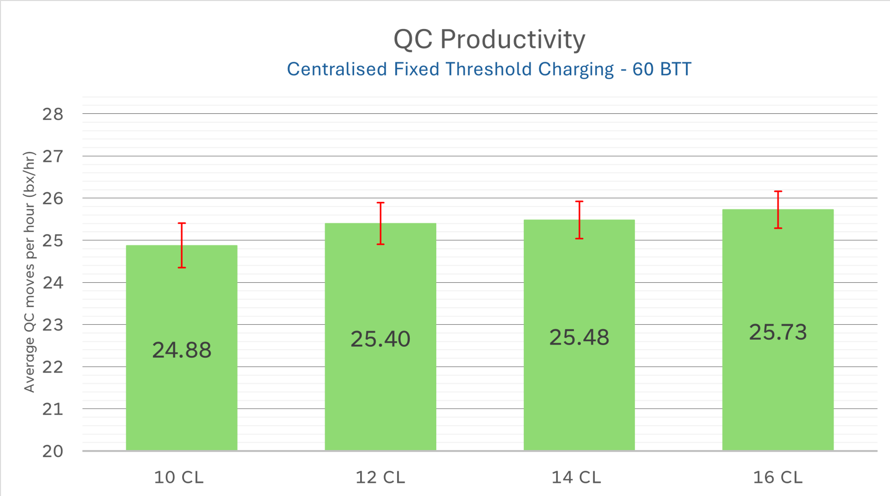


Figure 6.6: QC productivity Centralised Fixed Threshold Charging

QC productivity (box/hr)				
Centralised Fixed Threshold Charging	10 CL	12 CL	14 CL	16 CL
Average	24.88	25.40	25.48	25.73
95% Confidence	±0.53	± 0.50	± 0.44	± 0.44

Table 6.3: QC productivity Centralised Fixed Threshold Charging

Figure 6.7 shows the cost estimation for the Centralised Fixed Threshold Charging configurations. This strategy utilises the cheaper BTTs with a smaller battery as presented in Table 5.4 throughout all configurations. With the number of increasing charge lanes, the investment cost for these subsequently increases. Something interesting occurs when focusing on the operational cost of the different configurations. Because the same number of BTTs operate in all these configurations and due to a higher QC productivity for the configurations with more charge lanes the number of operating hours decreases resulting in a lower operational cost. This has the effect that the initial extra investment in extra chargers is compensated by a lower operational cost resulting in an overall lowest cost for the 16 CL configuration.

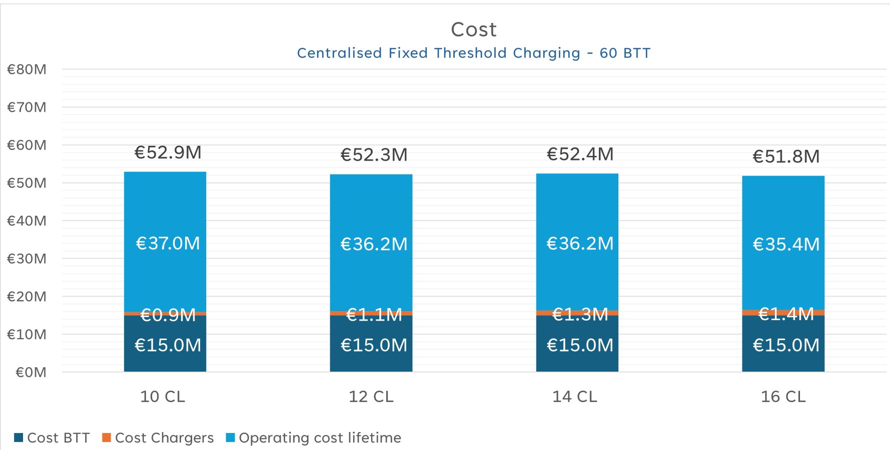


Figure 6.7: Cost estimation Centralised Fixed Threshold Charging

Figure 6.8 and Figure 6.9 provide some insight into the BTT status and the average charge lane utilisation for the CFT configurations. It is clear from the first figure that for the configuration with only 10 charge lanes the BTTs spent some time waiting for an available charger. This is also confirmed by the average charge lane utilisation presented in the second figure. The number of charge lanes is not sufficient to handle the demand of vehicles and is close to its maximum occupation throughout the shift. With an increasing number of available charge lanes the percentage of time a BTT has to wait for an available charger decreases. Interesting to note is that with the fixed charging strategy many vehicles occupy the charge lanes at one moment after which the total demand for charging decreases. This could be the effect of multiple vehicles reaching the charge threshold around the same time cluttering the chargers. After this a large group of vehicles is fully charged again, decreasing the overall need for charging.

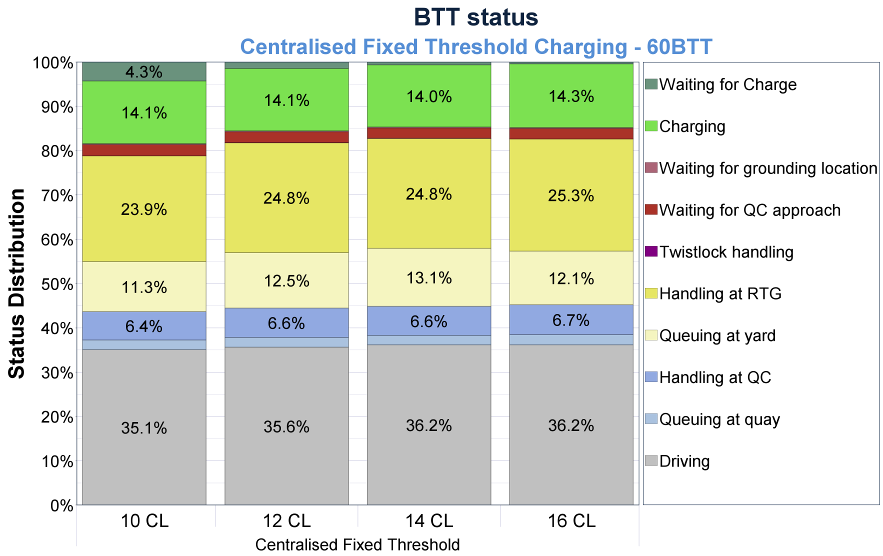


Figure 6.8: BTT status CFT

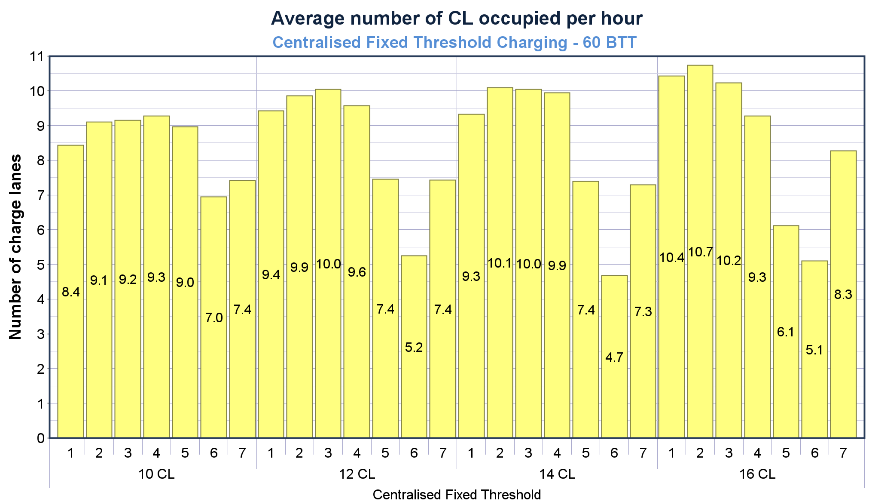


Figure 6.9: Average Charge lane utilisation CFT

6.1.4. DA3: Decentralised Fixed Threshold Charging (DFT)

To test the performance of the Decentralised Fixed Threshold Charging strategy experiments 9,10, 11 and 12 were conducted. During these experiments, the effect of charge lane location was investigated.

Figure 6.10 and Table 6.4 show a slight improvement in the QC productivity compared to the CFT alternative, although not statistically significant. Any statistically significant improvement within the strategy is observed between the configuration of 10 CL and 14 or 16 CL. Noteworthy is the fact that for this strategy both the configuration with 14 as well as 16 CL have an average QC productivity close to that of the 50 TT benchmark.

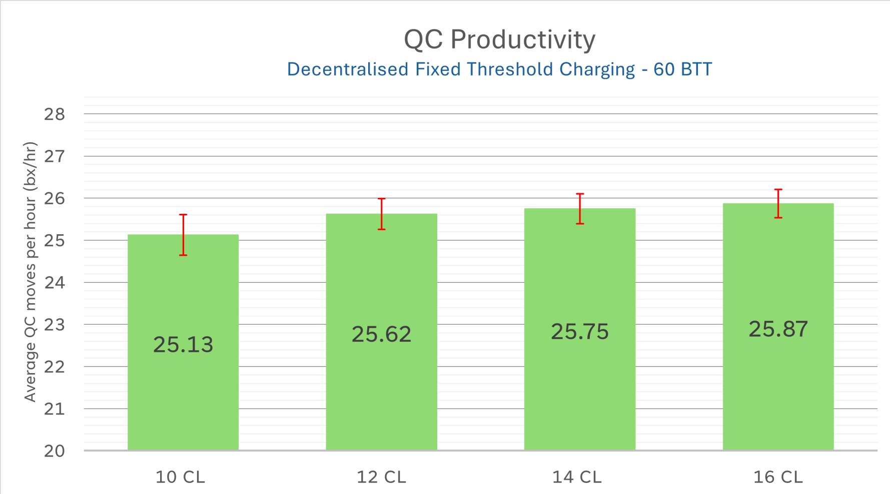


Figure 6.10: QC productivity Decentralised Fixed Threshold Charging

QC productivity (box/hr)				
Decentralised Fixed Threshold Charging	**10 CL**	**12 CL**	**14 CL**	**16 CL**
Average	25.13	25.62	25.75	25.87
95% Confidence	$\pm$0.48	$\pm$0.37	$\pm$0.36	$\pm$0.34

Table 6.4: QC productivity Decentralised Fixed Threshold Charging

Figure 6.11 provides the cost estimation for the Decentralised Fixed Threshold Charging strategy. Due to the need for multiple charging locations in this strategy, the investment cost for the charge lanes has been increased by 20% accounting for extra electrical connection. Again the relationship between higher QC productivity and lower operational costs for the same BTT fleet size is visible, although the effect is not enough to offset the extra investment cost for extra chargers in the 14 and 16 CL configurations.

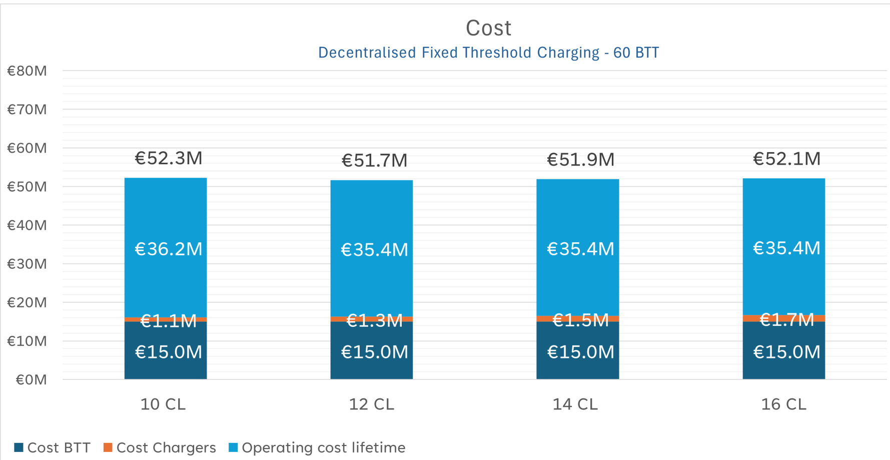


Figure 6.11: Cost estimation Decentralised Fixed Threshold Charging

Figure 6.12 and Figure 6.13 provides some insight in the BTT status and the average charge lane utilisation for the DFT configurations. It is clear that for the configuration with 10 charge lanes some time is spent by the BTTs waiting for an available charge lane, although it is slightly less compared to the CFT configurations. This waiting for charging decreases with the addition of extra charging lanes. The charge lane utilisation shows a similar relationship to CFT configurations with large fluctuations in occupation rate.

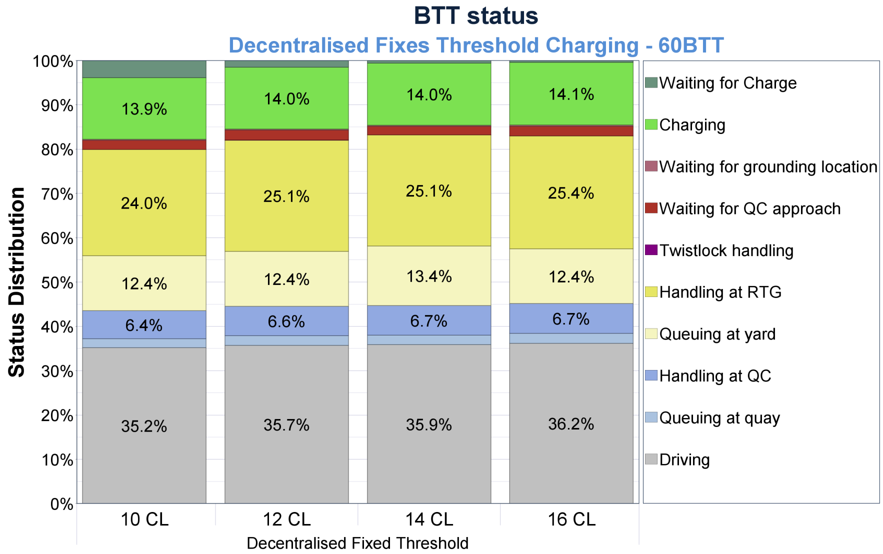


Figure 6.12: BTT status DFT

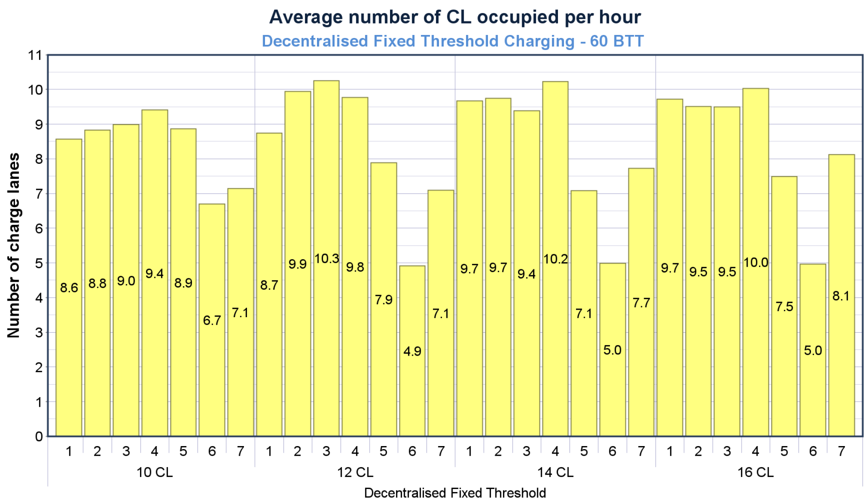


Figure 6.13: Average Charge lane utilisation DFT

6.1.5. DA4: Decentralised Pre-Emptive Charging (DPE)

To test the performance of the Decentralised Pre-Emptive Charging strategy experiments 13,14,15 and 16 were conducted. During these experiments, the effect of Pre-Emptive charging with a dynamic charge threshold was investigated.

Figure 6.14 and Table 6.5 show the QC productivity of the Decentralised Pre-Emptive charging configurations. A slight improvement in productivity, compared to DFT, is observed although only statistically significant for the configuration with 16 charge lanes. A statistically significant improvement within the strategy is observed between the configuration of 10 CL and 12, 14 or 16 CL. Furthermore, a statistically significant improvement is observed between the configuration of 12 and 16 charge lanes. Finally, for this charging strategy the configurations with 12, 14 and 16 CL have an average QC productivity exceeding that of the 50 TT benchmark.

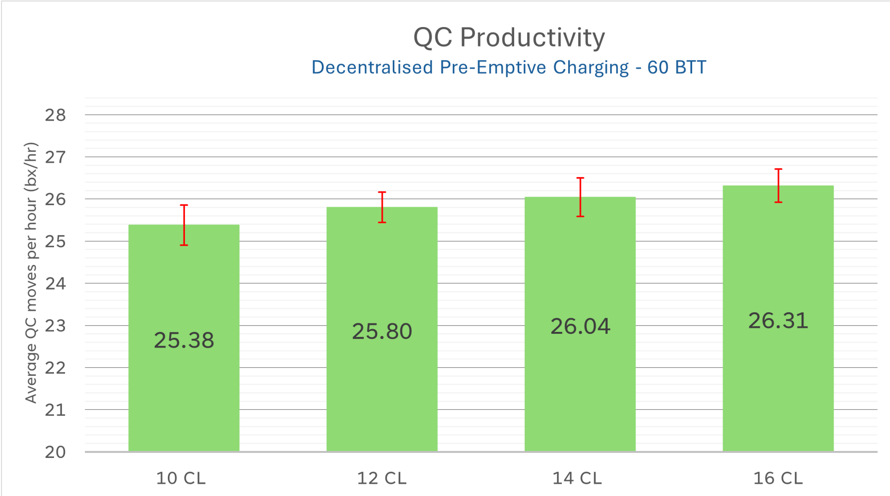


Figure 6.14: QC productivity Decentralised Pre-Emptive Charging

QC productivity (box/hr)				
Decentralised Pre-Emptive Charging	**10 CL**	**12 CL**	**14 CL**	**16 CL**
Average	25.38	25.80	26.04	26.31
95% Confidence	$\pm$0.48	$\pm$0.36	$\pm$0.46	$\pm$0.39

Table 6.5: QC productivity Decentralised Pre-Emptive Charging

Figure 6.15 provided the cost estimation for the Decentralised Pre-Emptive charging strategy. Investment cost in chargers and BTTs is identical to that of the DFT configurations. Again the relationship between higher QC productivity and lower operational costs for the same BTT fleet size is visible, the effect is enough to offset the extra investment cost for extra chargers in the 12 and 16 CL configurations. This results in the smallest total cost for the 16 CL configuration.

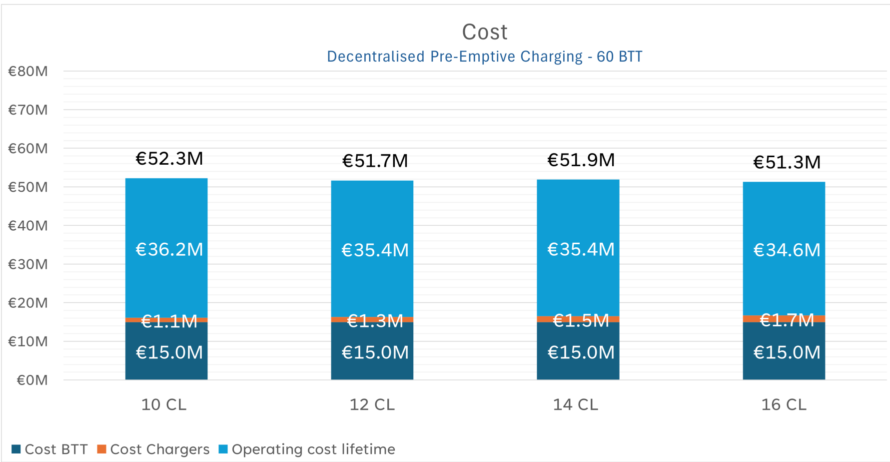


Figure 6.15: Cost estimation Decentralised Pre-Emptive Charging

The effect of the pre-emptive charging policy becomes visible when looking at Figure 6.16 and Figure 6.17. When utilising a significant number of charge lanes, from 10 CL upwards, waiting for charging is brought down to a minimum. The dynamic charge threshold applied ensures that the charging of BTTs is in line with the current energy need of that fleet and vehicles are ordered to charge pre-emptively when a drop in average fleet SoC is detected. Charging is spread out throughout the shift, resulting in little waiting time, as can be seen in Figure 6.17. This decrease in waiting on charging ultimately results in the BTTs spending a smaller amount of time out-of-service resulting in higher QC productiveness.

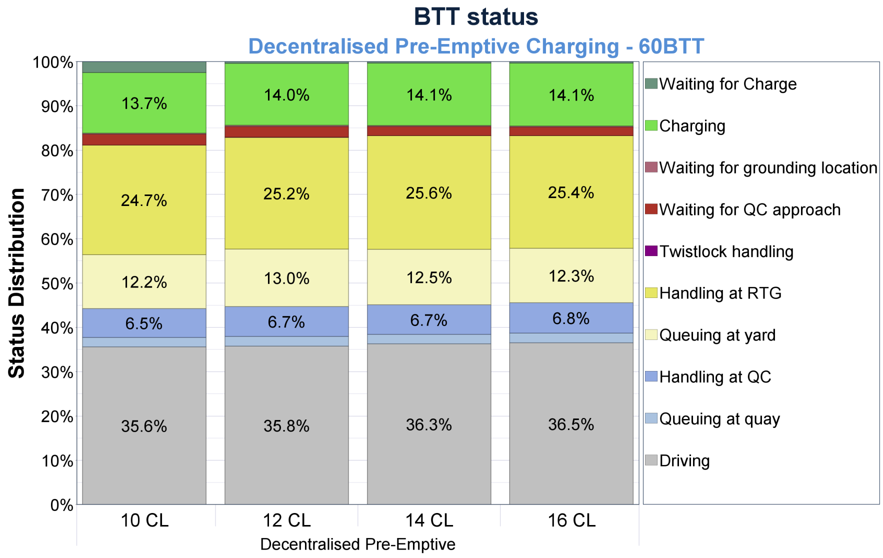


Figure 6.16: BTT status DPE

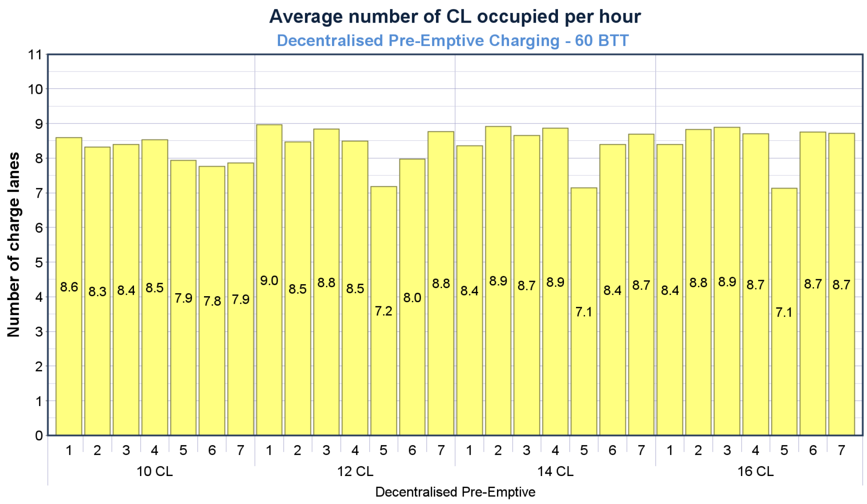


Figure 6.17: Average Charge lane utilisation DPE

6.1.6. DA5: Decentralised Opportunity Charging (DOP)

During the final experiment, 17, the performance of the Decentralised Opportunity Charging charging strategy was investigated. A fleet of 50 BTTs is fast-charged at the RTGs. Following the results of experiment 4, the amount of energy with which the battery of the BTT is replenished is set at 4.6 kWh.

Figure 6.18 and Table 6.6 show the QC productivity of the Decentralised Opportunity Charging strategy. Because charging happens during container handling operations at the RTG it does not affect the QC productivity. Consequently, the QC productivity of the Decentralised Opportunity charging strategy is similar to that of the 50 TT diesel benchmark.

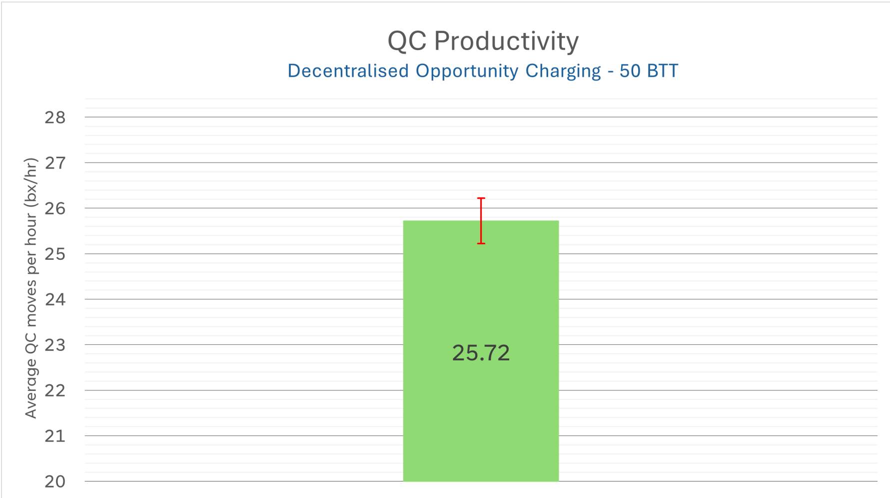


Figure 6.18: QC productivity Decentralised Opportunity Charging

QC productivity (box/hr)	
Decentralised Opportunity Charging	
QC productivity	25.72
95% Confidence	$\pm$0.50

Table 6.6: QC productivity Decentralised Opportunity Charging

A more intriguing aspect is the total cost associated with implementing the Decentralised Opportunity Charging strategy. As shown in Figure 6.19, it is clear that the investment in high-capacity wireless chargers for each RTG leads to substantial infrastructure costs. When combined with the investment required for the fleet of BTTs, this accounts for nearly half of the total cost. Overall the total cost of the DOP strategy is the highest of all the battery-powered RTG terminal configurations.

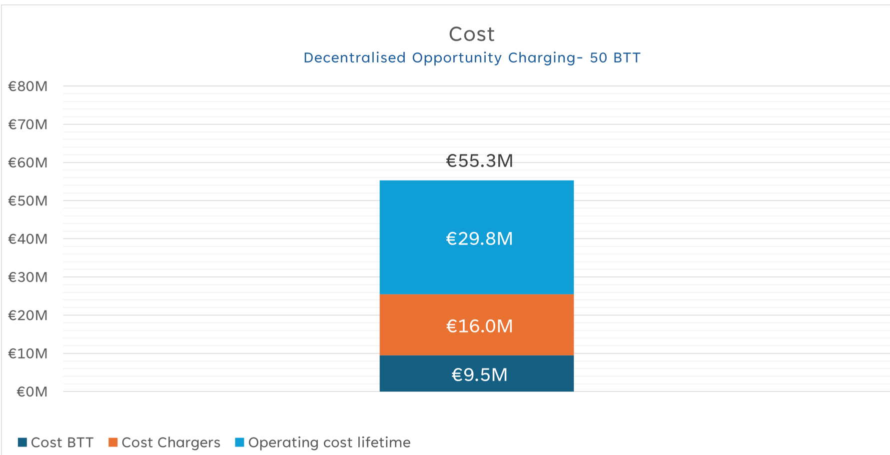


Figure 6.19: Cost estimation Decentralised Opportunity Charging

Finally, Figure 6.20 illustrates the state of charge (SoC) over time for a selection of the BTTs. The SoC of each vehicle was recorded at five-minute intervals. Initially, the BTTs had a state of charge ranging between 80% and 90%. Over time, they underwent multiple cycles of discharging and recharging. During each RTG visit, the BTTs received partial recharges. Since each BTT was recharged with the same amount of energy, regardless of individual consumption, a disbalance developed over time, leading to some vehicles being undercharged while others were overcharged.

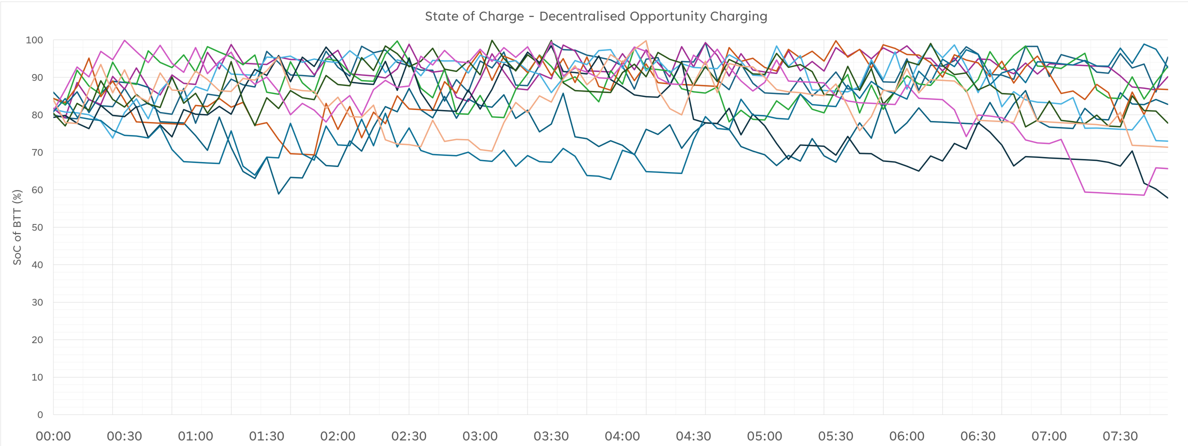


Figure 6.20: BTT SoC over time Decentralised Opportunity Charging

6.2. Comparative analysis

6.2.1. All experiments

Figure 6.21 and Table 6.7 provide an overview of the average QC productivity for each of the tested configurations. When comparing the average productivity across different charging strategies, there is little statistically significant difference, except for CFT-10 CL which performs significantly poorer than most alternatives and DPE-16 CL, which outperforms most other alternatives. Although the differences are mostly not statistically significant, a slight improvement in productivity is observed between Design Alternatives 2, CFT, 3, DFT, and 4, DPE, with decentralised charging using a dynamic charge threshold performing best (see section B.2). Design Alternative 1, OOP and 5, DOP perform similarly to the 50 TT benchmark. This is as expected because the charging of BTTs does not influence the QC productivity.

Several configurations meet or exceed the target average QC productivity of 25.73 bx/hr, with only Design Alternative 2, CFT - 10 CL and Design Alternative 3, DFT - 10 CL falling short with statistical significance. All charging strategies show statistically significant improvements over the 40 TT benchmark, but none reach the performance level of the 60 TT benchmark.

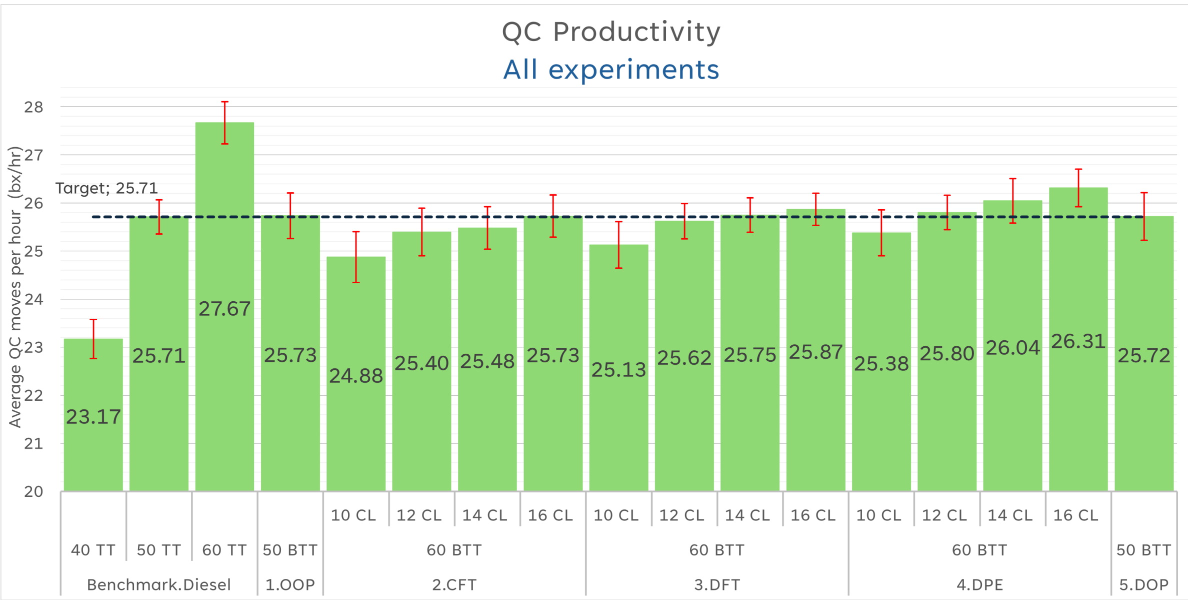


Figure 6.21: QC productivity all experiments

	QC productivity (box/hr)																
DA	Diesel			OOP	CFT				DFT				DPE				DOP
Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Average	23.17	25.71	27.67	25.73	24.88	25.40	25.48	25.73	25.13	25.62	25.75	25.87	25.38	25.80	26.04	26.31	25.72
95% Confidence	±0.41	±0.35	±0.44	±0.48	±0.53	±0.50	±0.44	±0.44	±0.48	±0.37	±0.36	±0.34	±0.48	±0.36	±0.46	±0.39	±0.50

Table 6.7: QC Productivity all experiments

Figure 6.22 gives the cost estimation for each of the tested configurations. Due to the high operating cost, resulting from high fuel and maintenance costs, the benchmark diesel configurations are the most expensive. Despite significant BTT and charger investment costs the Out of Operations OOP strategy is the cheapest alternative. The equipment investment cost of the CFT, DFT and DPE strategies are similar with the decentralised alternatives costing slightly more in terms of cost for charging infrastructure. As mentioned before, the operational cost of the different configurations with the same BTT fleet size decreases with increasing QC productivity. This is due to the same amount of vehicles operating more efficiently. Regarding the DOP strategy, it is clear that the investment in high-capacity wireless chargers for each RTG leads to substantial infrastructure costs. When combined with the investment required for the fleet of BTTs, this accounts for nearly half of the total cost. Overall the total cost of the DOP strategy is the highest of all the battery-powered RTG terminal configurations.

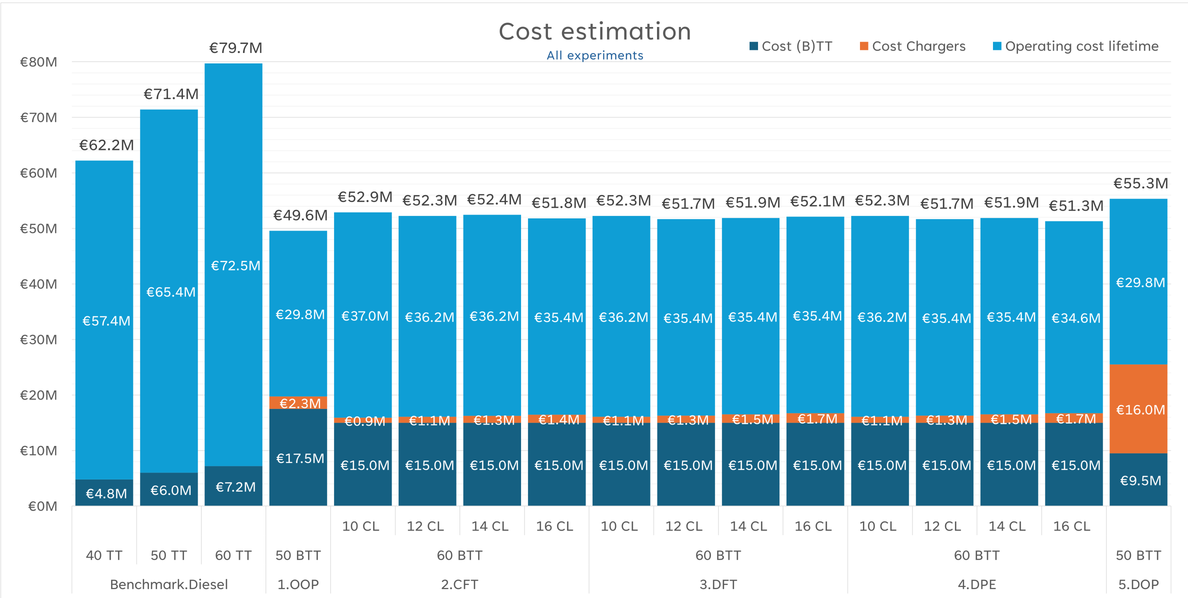


Figure 6.22: Cost estimation all experiments

6.2.2. Productivity versus Diesel Benchmark

A comparison of the productivity has been made between the different charging strategies and the diesel-powered benchmarks. Table 6.8 presents the differences in QC productivity between the different charging strategies and the benchmark diesel options. A paired t-test was performed to test statistical significance. The results are shown in Table 6.9. P-values below 0.05 indicate a statistically significant difference in QC productivity, while P-values above 0.95 suggest a statistically significant comparable average QC productivity. The former is crucial for demonstrating a significant decrease or improvement in performance, while the latter indicates a strong comparable performance. For P-values in between the comparison is inconclusive.

Based on the results in the tables, it is evident that each charging strategy performs significantly better than the 40 TT diesel benchmark but falls significantly short of the 60 TT benchmark. Only looking at the comparison with the 50 diesel TTs, several observations can be made. The QC productivity of the DOP strategy, as well as the CFT - 16 CL configuration, is statistically comparable to the 50 TT benchmark. The QC productivity of the OOP strategy is strongly comparable to that of the 50 TT diesel benchmark although it falls slightly short of being statistically significant with a P-value of 0.91.

The CFT and DFT strategies with 10 charging lanes perform statistically worse than the 50 TT benchmark. The DPE - 16 CL configuration is the only one that statistically outperforms the 50 TT diesel benchmark. For all other charging strategy configurations, there is no statistical evidence to conclude whether their performance is worse, equal to, or better than that of the 50 TT diesel benchmark.

			QC productivity Difference (box/hr)													
			OOP	**CFT**				**DFT**				**DPE**				**DOP**
				10 CL	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	
		QCR	**25.73**	**24.88**	**25.4**	**25.48**	**25.73**	**25.13**	**25.62**	**25.75**	**25.87**	**25.38**	**25.8**	**26.04**	**26.31**	**25.72**
Diesel	*40 TT*	**23.17**	2.56	1.71	2.23	2.31	2.56	1.96	2.45	2.58	2.7	2.21	2.63	2.87	3.14	2.55
	50 TT	**25.71**	0.02	-0.83	-0.31	-0.23	0.02	-0.58	-0.09	0.04	0.16	-0.33	0.09	0.33	0.6	0.01
	60 TT	**27.67**	-1.94	-2.79	-2.27	-2.19	-1.94	-2.54	-2.05	-1.92	-1.8	-2.29	-1.87	-1.63	-1.36	-1.95

Table 6.8: QC productivity versus Benchmark

		QC productivity paired T-Test P-values													
		OOP	**CFT**				**DFT**				**DPE**				**DOP**
			10 CL	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	
Diesel	*40 TT*	1.18E-12	9.69E-09	3.02E-11	1.11E-11	3.45E-13	1.88E-09	6.62E-13	2.10E-12	1.04E-13	2.17E-09	1.39E-12	1.03E-14	1.15E-14	9.31E-13
	50 TT	0.91	0.00	0.16	0.22	0.95	0.02	0.65	0.84	0.38	0.18	0.66	0.16	0.01	0.97
	60 TT	4.47E-08	5.31E-13	2.73E-09	1.38E-09	1.12E-08	7.21E-10	1.21E-08	2.06E-10	7.36E-08	2.60E-08	2.87E-08	4.82E-07	9.59E-07	4.48E-08

Table 6.9: Paired T-Test P-Values

6.2.3. QC Productivity versus Costs

With the data from Table 6.7 and Figure 6.22 a scatter plot was made to illustrate the relationship between QC productivity and total lifetime costs. Figure 6.23 shows the QC productivity and the corresponding costs for each of the configurations. A Pareto Front is added to illustrate the best performance at each cost level [37]. It can be used to select appropriate configurations based on performance or cost implications.

If total cost is most important the lowest cost level has to be selected. At the lowest cost level of €49.6M the best performing configuration is Out of Operations with an average QC productivity of 25.73 box/hr. Next, with a total cost of €51.3M, the Decentralised Pre-Emptive - 16 Cl configuration has an average QC productivity of 26.31 box/hr. This configuration is a good balance between performance and costs. If maximum QC productivity is critical, the Diesel 60 TT benchmark performs best. But this also results in the highest costs of €79.7M.

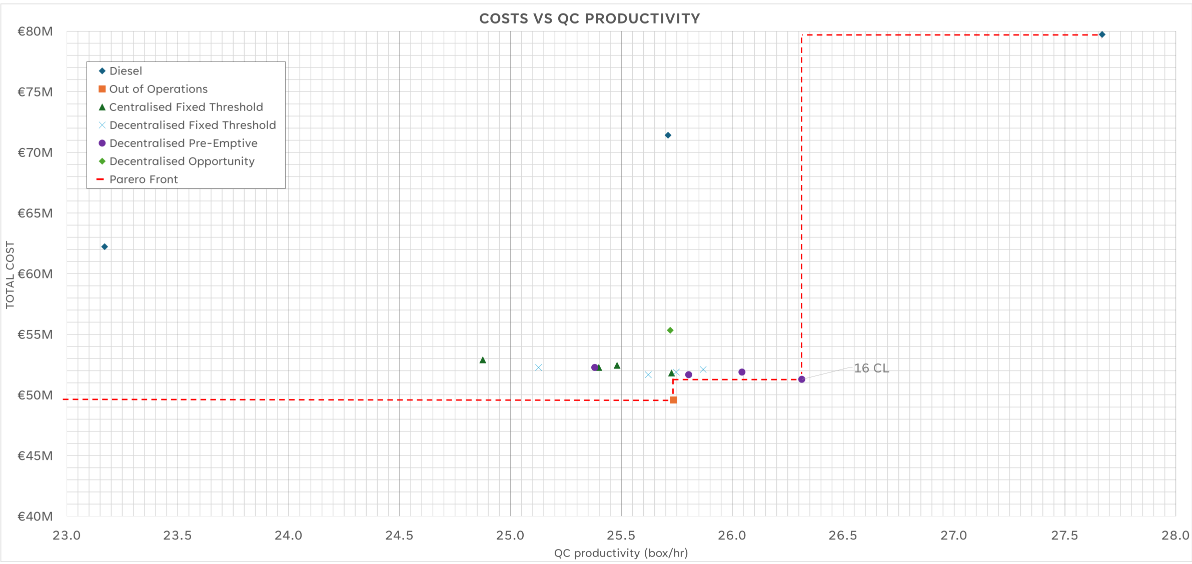


Figure 6.23: QC productivity vs Costs

6.3. Conclusion

This chapter discussed the results of the experiments conducted during this research. It presented the average QC productivity calculated from the simulations of various charging strategies, as well as cost estimations for the different configurations. Additionally, when relevant, other performance indicators, such as BTT status, state of charge (SoC) over time, and energy consumption for the different strategies, were also provided.

An answer was provided to sub-question 7:*How do the different charging strategies, both in configuration and operation, perform?* The performance of different charging strategy configurations, shows minimal statistically significant differences in average productivity. The exception is the CFT - 10 CL configuration, which performs significantly worse than most alternatives at 24.88 box/hr, and the DPE - 16 CL configuration, which outperforms most others at 26.31 box/hr. Although most differences are not statistically significant, a QC productivity improvement is observed between Design Alternatives 2 CFT, 3 DFT, and 4 DPE, particularly with decentralised charging using a dynamic charge threshold (see section B.2) with a productivity improvement of 0.52 boxes/hr over CFT. The OOP and DOP strategies perform similarly to the 50 TT benchmark at 25.73 and 25.72 box/hr respectively. This was expected since the charging of BTTs does not significantly impact QC productivity.

Finally, sub-question 8 was answered *How do the productivity and cost of different charging strategies compare to diesel-powered RTG terminals?* The productivity of different charging strategies, when compared to diesel-powered RTG terminals, was assessed using a paired t-test to determine statistical significance. The results showed that all charging strategies performed significantly better than the 40 TT benchmark but fell short of the 60 TT benchmark. The QC productivity of the DOP strategy (25.72 box/hr), as well as the CFT - 16 CL configuration (25.73 box/hr), is statistically comparable to the 50 TT benchmark (25.71 box/hr). The QC productivity of the OOP strategy, at 25.73 box/hr, is strongly comparable to that of the 50 TT diesel benchmark although it falls slightly short of being statistically significant with a P-value of 0.91. However, the CFT and DFT strategies with 10 charging lanes performed statistically worse than the 50 TT benchmark at 24.88 and 25.13 box/hr, while the DPE - 16 CL configuration was the only one to statistically outperform it at 26.31 box/hr. For other charging strategies, the paired t-test provided no statistical evidence to determine whether their productivity was better, worse, or equal to that of the 50 TT benchmark.

Due to the high operating cost, resulting from high fuel and maintenance costs, the 60 TT benchmark diesel configuration is the most expensive at €79.7M. Despite significant BTT and charger investment costs the Out of Operations OOP is the cheapest alternative with a total cost of €49.6M. The equipment investment cost of the CFT, DFT and DPE strategies are similar with the decentralised alternatives costing slightly more in terms of cost for charging infrastructure. As mentioned before, the operational cost of the different configurations with the same BTT fleet size decreases with increasing QC productivity. This is due to the same amount of vehicles operating more efficiently. Regarding the DOP strategy, it is clear that the investment in high-capacity wireless chargers for each RTG leads to substantial infrastructure costs of €55.3M. When combined with the investment required for the fleet of BTTs, this accounts for nearly half of the total cost. Overall the total cost of the DOP strategy is the highest of all the battery-powered RTG terminal configurations.

It is important to acknowledge that the conclusions drawn are specific to the particular case studied and are based on assumed values for parameters such as fuel, energy, and vehicle costs. Consequently, these results and conclusions may not be true for all RTG terminals.

7 Conclusion

In this chapter, the final conclusions of the thesis are presented, addressing the main research question:*"What is the effect of charging strategies for battery-powered terminal trucks on the productivity and cost of an RTG-based container terminal?"* To comprehensively address this question, eight sub-questions were developed. First, the responses to these sub-questions are presented, and then a conclusive answer to the main research question is provided.

7.1. Conclusion

Sub-Question 1: **What activities and functions are performed within container terminals?** Container terminals are vital in the supply chain network, linking deep-sea transport with other transportation modes and serving as distribution nodes between producers and consumers. These terminals primarily function to load and unload containers from deep-sea vessels onto feeder vessels, barges, trucks, and trains. There are three key functions within a terminal: transferring (lifting and placing), transporting, and storing containers. Container terminals consist of five main areas: the berth, quay, transport area, storage yard, and terminal gate. Quay Cranes at the seaside load and unload containers between vessels and the quay, while various horizontal transportation vehicles move containers between the yard and the quay in the transport area. The yard contains lanes for container storage, from where they are loaded onto different transport modes. Trucks pass through the gate to pick up and deliver containers, and barges can be handled alongside deep-sea vessels at the quay or dedicated barge quays. Additionally, many terminals feature a rail terminal for loading and unloading containers from trains. A common type of container terminal is the RTG terminal, which uses terminal trucks and rubber tired gantry cranes.

Sub-Question 2: **What are the characteristics and operational profile of battery-powered terminal trucks?** Battery-powered terminal trucks operate similarly to diesel variants, with the key difference being that they are powered by an internal battery that needs to be charged when depleted. During accelerating and constant driving electrical energy is used from the batteries, whilst during decelerating some energy can be regenerated resulting in some recuperated energy. Charging can be done at several types of charging infrastructure. The chargers are either wired, inductive or use a conductive contact pad. Different manufacturers produce types of BTTs with varying motor powers and battery capacities. A larger battery capacity with a low motor power ensures longer operation periods.

Sub-Question 3: **Which charging strategies for battery-powered vehicles are proposed in the literature?** During a literature review different charging strategies proposed in the literature were investigated. The charging strategies included a combination of four different charging policies: Non-operating hours, Fixed Threshold, Opportunity and Pre-Emptive charging and two charging infrastructure methods: conductive or inductive.

Sub-Question 4: **What are possible design alternatives for charging battery-powered terminal trucks?** Five different design alternatives for charging battery-powered container terminal trucks are presented. These design alternatives are Out of Operations Charging, Fixed Threshold Centralised Charging, Fixed Threshold Decentralised Charging, Decentralised Pre-Emptive Charging and Decentralised Opportunity Charging.

Sub-Question 5: **How can the operation of a container terminal, including the operational profile and charging of battery-powered terminal trucks, be represented by a model?** The model representing the battery-powered BTT operation in an RTG terminal includes the energy consumption during driving, regenerative braking and accelerating and updates the SoC of the BTT accordingly for every timestep. Furthermore, it includes different charging infrastructures comprising of wired or inductive charging methods. Combined with implementing different charging policy rules this results in a model representing charging strategies that simulate operations and charging of BTTs.

Sub-Question 6: **How can the different charging strategies be implemented and tested in a terminal operation simulation model?**

By applying specific terminal configuration settings and incorporating BTT driving and power consumption parameters, experiments are designed to evaluate the practical implementation and performance of various charging strategies within an RTG terminal operation simulation.

Key performance indicators (KPIs), such as QC productivity and cost, and additional performance metrics can assess the effectiveness of each strategy. This approach allows for a detailed comparison of strategies, considering variables such as charger locations, charging policies, charging capacities, and the number of available charging lanes.

Sub-question 7:**How do the different charging strategies, both in configuration and operation, perform?**

The performance of different charging strategy configurations shows minimal statistically significant differences in average productivity. The exception is the CFT - 10 CL configuration, which performs significantly worse than most alternatives at 24.88 box/hr, and the DPE - 16 CL configuration, which outperforms most others at 26.31 box/hr. Although most differences are not statistically significant, a QC productivity improvement is observed between Design Alternatives 2 CFT, 3 DFT, and 4 DPE, particularly with decentralised charging using a dynamic charge threshold (see section B.2) with a productivity improvement of 0.52 boxes/hr over CFT. The OOP and DOP strategies perform similarly to the 50 TT benchmark at 25.73 and 25.72 box/hr respectively. This was expected since the charging of BTTs does not significantly impact QC productivity.

Sub-question 8:**How do the productivity and cost of different charging strategies compare to diesel-powered RTG terminals?**

The productivity of different charging strategies, when compared to diesel-powered RTG terminals, was assessed using a paired t-test to determine statistical significance. The results showed that all charging strategies performed significantly better than the 40 TT benchmark but fell short of the 60 TT benchmark. The QC productivity of the DOP strategy (25.72 box/hr), as well as the CFT - 16 CL configuration (25.73 box/hr), is statistically comparable to the 50 TT benchmark (25.71 box/hr). The QC productivity of the OOP strategy, at 25.73 box/hr, is strongly comparable to that of the 50 TT diesel benchmark although it falls slightly short of being statistically significant with a P-value of 0.91. However, the CFT and DFT strategies with 10 charging lanes performed statistically worse than the 50 TT benchmark at 24.88 and 25.13 box/hr, while the DPE - 16 CL configuration was the only one to statistically outperform it at 26.31 box/hr. For other charging strategies, the paired t-test provided no statistical evidence to determine whether their productivity was better, worse, or equal to that of the 50 TT benchmark.

Due to the high operating cost, resulting from high fuel and maintenance costs, the 60 TT benchmark diesel configuration is the most expensive at €79.7M. Despite significant BTT and charger investment costs the Out of Operations OOP is the cheapest alternative with a total cost of €49.6M. The equipment investment cost of the CFT, DFT and DPE strategies are similar with the decentralised alternatives costing slightly more in terms of cost for charging infrastructure. As mentioned before, the operational cost of the different configurations with the same BTT fleet size decreases with increasing QC productivity. This is due to the same amount of vehicles operating more efficiently. Regarding the DOP strategy, it is clear that the investment in high-capacity wireless chargers for each RTG leads to substantial infrastructure costs of €55.3M. When combined with the investment required for the fleet of BTTs, this accounts for nearly half of the total cost. Overall the total cost of the DOP strategy is the highest of all the battery-powered RTG terminal configurations.

To conclude this work provides an answer to the main research question: **”What is the effect of charging strategies for battery-powered terminal trucks on the productivity and costs of an RTG container terminal?”**

The work performed during this research demonstrates that the choice of charging strategy for battery-powered terminal trucks significantly influences both the productivity and cost of an RTG container terminal.

It has been found that when employing strategies such as Out of Operation and Decentralised Opportunity Charging, BTT charging does not negatively impact terminal productivity with a QC productivity of 25.73 box/hr and 25.72 box/hr respectively. The performance metrics for these strategies are statistically comparable to those of terminals utilising the same number of diesel-powered terminal trucks (25.71 box/hr).

However, with charging during container handling operations additional vehicles are needed, due to the downtime required for charging, leading to the need for supplementary vehicles to maintain performance similar to a smaller fleet of diesel-powered terminal trucks. The study also highlights that while the location of charging stations provides a slight, though not statistically significant, improvement in QC productivity of 0.22 box/hr. A limited number of charging lanes, results in increased waiting on charging times. This, in turn, reduces BTT availability and adversely affects QC productivity.

The implementation of a decentralised pre-emptive charging strategy with a dynamic charge threshold emerges as a promising strategy, as it minimises charge waiting times and BTT idle periods, thus enhancing QC productivity (strategy average of 25.89 box/hr) whilst also stabilising charge lane utilisation. Conversely, central charging with a fixed threshold and limited charging lanes strongly impairs QC productivity. Increasing the number of available charge lanes increases QC productivity.

Despite the higher upfront vehicle and infrastructure investments required, battery-powered terminal trucks offer the advantage of lower operational costs over their lifetime compared to diesel alternatives. Particularly, out of operations charging is the most cost-effective strategy at €49.6M, provided the terminal has sufficient downtime to accommodate simultaneous vehicle charging. On the other hand, decentralised opportunity charging incurs the highest costs of the battery-powered configurations at €55.3M. This is primarily due to the substantial investment needed for high-capacity wireless charging infrastructure.

Taking both QC productivity and total cost into consideration, the study concludes that decentralised pre-emptive charging with a large number of charge lanes is the optimal strategy. This approach not only statistically significantly outperforms some diesel benchmarks in terms of QC productivity, at 26.31 box/hr, but also has a low total cost, €51.3M, by maximising operational efficiency and minimising operating expenses. Thus, for RTG-based terminals aiming to balance productivity with cost-effectiveness, this strategy stands out as the most viable and advantageous solution.

8 Discussion

8.1. Reflection

The RTG/BTT model and subsequent simulations developed during this research were able to simulate the operations of battery-powered terminal trucks, including charging within the RTG terminal. It serves as a good basis for testing the effect of different charging strategies, although it has its shortcomings.

Little statistically significant difference between charging strategies was observed, this could be because how the charging strategies were implemented and tested was not sufficient enough to test the actual effect of adopting different strategies in RTG terminals. Furthermore, the productivity of the QC was also susceptible to congestion within the terminal not necessarily caused by a charging strategy. More effort could have been spent on isolating the impact of the different strategies to reach more conclusive results.

To reach more statistically significant differences in performance for in-operation charging, the variation in the number of available chargers could have been bigger. Incrementally increasing the number of available chargers by 2 CIs for the CFT, DFT and DPE configurations resulted in similar performance and small noticeable improvements.

Also, due to the absence of real-life data on energy consumption and equipment cost it is difficult to confirm the validity of the results as presented in this research. A different energy consumption could present large implications on the effectiveness of one of the proposed charging strategies.

Finally, it is important to note that the conclusions drawn in this research are specific to a particular case studied and are based on assumed values for key parameters, including fuel, energy, and vehicle costs. As a result, the findings and conclusions presented may not be universally applicable to all RTG terminals. The performance of other RTG terminals may vary depending on differences in operational conditions, energy consumption patterns, and cost estimations.

8.2. Recommendations

Based on the findings of this thesis, further research is recommended to evaluate the impact of charging strategies on the performance of battery-powered terminal trucks.

1. Alternative Terminal Layouts: Explore larger terminal layouts to assess the effect of travel distance to charging stations on overall terminal performance. In the current setup, the impact of travel distance is minimal, as any time lost or gained is relatively insignificant compared to the total time required for charging. Testing in larger terminals may reveal more significant effects on operational efficiency.

2. Testing Charging Strategies in Real-life RTG Terminal Setups: Conduct research on charging strategies within an actual RTG terminal setup, using a specific terminal with known energy consumption, cost estimations for battery-powered terminal trucks (BTTs), and realistic fleet size. This approach will allow for a more accurate assessment of the true impact of switching to battery-powered trucks on a large scale. Currently, there is limited knowledge about the actual costs and practical implications of such a transition, and this research would provide valuable insights.

3. Effect of Battery Size and Charger Capacity: Investigate the relationship between battery size, charger capacity, and the balance between charge time and operational time for BTTs. Understanding how these factors interact will be crucial in optimising the charging process and ensuring that BTTs can operate efficiently without excessive downtime.

4. Development and Testing of Other Charging Strategies:

Linking Charging to Work Demand: Develop and test strategies that adjust charging based on work demand at the quay. For example, during slow periods in a shift, more charging can be scheduled, while during busy peaks, less charging would be allowed. This dynamic approach could help maintain operational efficiency while ensuring that BTTs are adequately charged.

Opportunity Charging with Dynamic Recharging: Explore the concept of opportunity charging, where the amount of recharge is dynamically adjusted to match the energy consumption needed for the next container handling operation of the BTT. This strategy could lead to more efficient use of available charging time and reduce the likelihood of BTTs being under or overcharged.

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A

Scientific Paper

The Effect of Charging Strategies For Battery-Powered Terminal Trucks on the Productivity and Costs of an RTG Terminal

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The adaptation of battery-powered terminal trucks (BTTs) in rubber tired gantry crane terminals (RTG) will affect terminal productivity and costs. This research tests the performance of different charging strategies and compares costs. This is done with the use of a discrete-event simulation model including the energy consumption and charging of BTTs. Five charging strategies are presented: Out of Operations (OOP), Centralised Fixed Threshold (CFT), Decentralised Fixed Threshold (DFT), Decentralised Pre-Emptive (DPE) and Decentralised Opportunity Charging (DOP). The scenarios were tested in a terminal operations model of an RTG terminal, with configurations varying in charge lane location and numbers. Based on productivity OOP and DOP performed similarly to a diesel-benchmark of the same fleet size. It was found that charge location has little effect on overall terminal performance when the charge duration is large. Pre-Emptive charging has a positive effect on terminal productivity through high charge lane utilisation and little time loss associated with waiting on available chargers. Due to lower energy and maintenance costs, all battery-powered alternatives are more cost-effective than diesel-powered alternatives.

1. Introduction

A changing climate and the effect of global warming are among some of the biggest challenges facing mankind. Consequently, industries have been pushed by international and regional institutions to reduce their greenhouse gas (GHG) emissions and become more sustainable. This is also true for the shipping and transportation industry. Unfortunately, the environmental impact the shipping of containers has does not stop when container vessels enter the port. The equipment used in ports is often powered by diesel or diesel hybrid engines, resulting in local air pollution. In 2010, Dutch research institute, TNO estimated that per TEU handled within Dutch container terminals, 4,5 litre diesel was needed (Dellaert [1]). Yu, Ge, Chen, *et al.* [2]'s research into the $CO2$ emissions of terminal tractors further adds to this stating that the pollution by this type of equipment is one of the main sources of pollution in maritime transport.Electrification of heavy-duty equipment is gaining momentum in a bid to fight global emissions. This deployment is driven partly by emission reduction policies and by energy use cost reductions (International Energy Agency [3]). Tethered container handling equipment can be powered by cable or bus bar. Batteries will power free-roaming equipment pieces. These batteries need to be charged or swapped when empty. This study focuses on the electrification and charging strategies of battery-powered terminal trucks (BTTs). Terminal trucks are widely used as a means of transporting containers within an Rubber Tired Gantry crane (RTG) terminal. Effectively switching to battery power for TTs could aid in cutting down GHG emissions and make container terminals more sustainable.

The adoption of battery-powered terminal trucks offers significant environmental benefits, but implementation remains limited due to several challenges. High upfront costs, including the need for specialised charging infrastructure, deter widespread use. Additionally, current charging practices—often waiting for batteries to deplete before recharging—cause operational downtime and require extra vehicles to maintain productivity. To fully realise the potential of battery-powered trucks, it is crucial to develop intelligent charging strategies that optimise energy efficiency, reduce downtime, and lower operational costs. Over-coming these challenges is essential for achieving sustainable container terminal operations.

Little research has been done into battery-powered terminal trucks as it is still an emerging technology. Work by Simpson, Asce, Thiessen, *et al.* [4] and Mohr, Kastner, and Jahn [5] investigates the importance and challenges of deploying battery-powered terminal trucks (BTTs) in container terminals. Both papers agree that the implication of employing battery-powered terminal trucks on a large scale is finding the correct charging strategies and the best positioning approach for charging stations. Although still challenging, all authors agree that due to the rise of diesel costs and the need to cut down on emissions, batteries are the way to go for terminal trucks. No specific research has been done on the performance of different charging strategies for BTTs.

This research aims to test different charging strategies for battery-powered container terminal trucks with the use of a large-scale terminal operation simulation. Using the simulations, the research will investigate the effect on the terminal performance of different charging strategies compared to benchmark diesel-powered operations. This leads to the research question of this research:

"What is the effect of charging strategies for battery-powered terminal trucks on the productivity and cost of an RTG container terminal?"

This question will be answered in this research, through the design of a BTT model that includes the operations and charging of BTTs. With this model simulation experiments have been performed featuring different charging strategies. The model was adopted into the TIMESQUARE terminal simulation environment of Portwise, which is made in the discrete-event simulation software eM-plant, to simulate the operations of driving and charging of BTTs within an RTG-based terminal. Preliminary to the design of these models, a system analysis of the RTG-based terminal and the BTT itself have been conducted, as well as a literature research on the charging strategies for all types of battery-powered container handling equipment.

2. Methodology

During this research two system analysis have been done. The first being the RTG terminal and its components and the second the battery-powered terminal trucks or BTTs. Next, a literature study on charging strategies for all types of battery-powered container handling equipment handling equipment. With this information several charging strategies have been adapted to be suited for BTTs. A model has been designed for discrete event simulation, the models include the operating and charging of BTTs. Finally, multiple experiments were conducted with different charging strategies for BTTs and a benchmark with diesel-powered terminal trucks using discrete-event simulation.

3. System Analysis

3.1. RTG terminal

The RTG terminal is a key focus in this research, characterised by the handling of containers through various types of container handling equipment (CHE). The terminal is typically divided into three main operational areas: the waterside, the storage yard, and the landside. See Figure 1 for a diagram of an RTG terminal. Containers enter and exit the terminal through both the quay and the gate at the landside, with import containers arriving by vessel and departing via external trucks (XTs), while export containers follow the reverse process. The gate of the terminal serves as the critical connection to the hinterland, where XTs enter to either pick up or drop off containers. Upon entry, XTs undergo a registration process, receive instructions, and have their containers inspected. At the quay, Quay Cranes (QCs), commonly single-trolley types, perform the crucial task of loading and unloading vessels. Diesel-powered Terminal Trucks (TTs), one of the most widely used equipment globally for horizontal transport, shuttle containers between QCs at the quay and Rubber Tired Gantry cranes (RTGs) are wheeled mobile gantry cranes, used in terminal operations to store containers in the stack. Horizontal transportation vehicles, predominantly terminal trucks, transfer containers between the RTG and the quay. The RTG drives over the stacking module, consisting of multiple rows and bays. When the RTG reaches the correct bay a transfer of container is made, it never travels over the stack with a container. The benefit of using RTGs for handling containers in the yard is the ability to move the crane between different stack modules. The RTG can exit one module and drive to another module to continue operations. This ensures high productivity and a low number of idle vehicles[6].

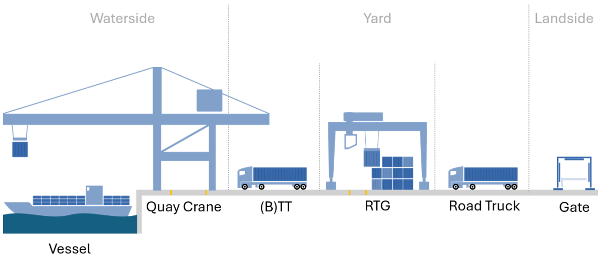

Figure 1. Diagram RTG-based Terminal

3.2. Battery-Powered Terminal Truck

3.2.1. *Characteristics Battery-Powered Terminal Truck*

The battery-powered terminal trucks have a similar operational profile to a standard diesel-powered one. They operate continuously, transporting containers between the RTG and the yard and the QC at the quay. Battery-powered variants require a high-energy capacity battery to ensure operation for long periods. During accelerating and constant driving electrical energy is used from the batteries, whilst decelerating some energy can be regenerated resulting in some recuperated energy.

Manufacturers of container terminal vehicles are increasingly coming up with battery-powered variants of terminal trucks [7][8][9]. The first battery-powered terminal trucks are slowly deployed at various terminals in the world [10][11]. Figure 2 shows a typical battery-powered terminal truck and Table 1 provides some basic characteristics of available models at different manufacturers.

Figure 2. Battery-powered Terminal Truck[12]

Manufacturer	Terberg	Kalmar	TICO	Gaussin	Sany
Model ID	YT200EB	TX22	Pro Spotter Electric	APM 75T	SM4600TOBEV
Battery recovery mode	Charge	Charge	Charge	Charge/Swap	Charge
Battery type	LFP	NMC	NMC/NCA	*	LFP
Battery capacity (kWh)	350	112 or 224	132	195/126	282
Operating period (h)	10	12 or 22	*	*	18
Charging period (h)	1	1 or 2	1	*	1.17
Charger Power (kW)	350	*	150	*	350
Motor Power (kW)	300	*	350	*	240

* unknown

Table 1. Characteristic Battery-Powered Terminal Trucks

3.2.2. *Charging Infrastructure*

Different types of charging infrastructure can charge the battery-powered terminal trucks.

Wired Stationary Charger

One option for charging battery-powered terminal trucks is to use wired stationary chargers at charging stations (CS) which have to be installed throughout the container terminal. The BTT is charged via a conductive connection. During charging the BTT remains idle and is unavailable for container operations. The adopted charging strategy determines the charging duration and required charging power. To achieve acceptable out-of-operation times an adequate number of chargers is needed. This often results in a large number of chargers scattered across the terminal.

Inductive Charger Another type of charging infrastructure is inductive charging. The benefit of this type of infrastructure is the absence of any above-ground equipment. A vehicle drives over coils embedded within the terminal surface and begins charging. A critical flaw of the inductive charging system is its low energy efficiency, resulting in extra charging costs. Applications of this have successfully been developed for city buses that drive pre-established routes.

This technology could be adapted to be suited for implementation within container terminals.

Current Collector Charger The final infrastructure is the current collector or pantograph. A technology that is often found on trains. Electric current collectors are typically made up of one or more spring-loaded arms that press a collector or contact shoe against a rail or overhead wire. The vehicle drives to a charging station equipped with a conductive pad. When the vehicle is in place the current collector is automatically extended and once contact is established, charging commences. The benefit of this system is that it is a well-developed technology in other fields and easily adapted to work in terminal operations. The downside is the need for a current collector at a height, above the vehicle. This will result in more possibilities for interference with other operations.

4. Literature Study

Charging strategies comprise a combination of charging infrastructure and a charging policy. The charging infrastructure determines how the batteries are physically charged. Charging policies determine when and for how long a battery is charged. A charging strategy has a deep impact on the system performance of a terminal. It is important that the charging of batteries does not negatively affect the overall performance of the terminal. A loss in production could result in higher costs for the terminal operator. To ensure this, a selected charging strategy must ensure little out-of-operation time for the battery terminal truck, at a reasonable investment cost.

4.1. Charging Strategies

4.1.1. Non-operating charging

The work of Simpson, Asce, Thiessen, *et al.* [4] presents the charging policy of in-vehicle non-operating charging. This first policy uses non-operating hours to recharge batteries and uses the energy obtained to run a full operating shift. Many charging locations, which are heavily used during non-operating periods, will be needed for this strategy. Additionally, this strategy might require larger batteries than necessary, increasing the equipment's initial cost. Research by Mohr, Kastner, and Jahn [5] into charging BTTs adds that this strategy is only effective in smaller container terminals with a small fleet of vehicles and a single shift per day. This *single-shift operation* depends on the ability of the fleet to contain enough battery capacity to operate the full shift.

4.1.2. Fixed Threshold Charging

As the authors Sun, Zhai, Li, *et al.* [13] describe in their work, for larger more advanced terminals non-operating charging is not a viable option. At these terminals, operations are often 24/7 with vehicles operating in multiple consecutive shifts. During a shift, the battery level of battery-powered equipment will become insufficient and energy replenishment is needed. A possible charging policy is a fixed threshold policy. With the fixed threshold charging policy, battery-powered vehicles are ordered to charge when the state of charge (SoC) reaches a predefined percentage of the total battery capacity. Charging is done during an operating shift. To ensure enough operational capacity extra vehicles are to be acquired.

4.1.3. Pre-Emptive Charging

The work by the authors Ma, Zhou, and Stephen [14] introduces the progressive, or pre-emptive, charging policy for charging battery-powered container terminal equipment. Compared to the fixed threshold policy, the progressive charging policy allows equipment to be charged more frequently when an idle charger is available. Before allocating a new job to a piece of equipment, the terminal operating system checks the SoC of all available pieces of equipment. If a piece of equipment has a SoC of less than 50% this vehicle is labelled as available to charge. The nearest three chargers are checked for availability. If a charger is available the vehicle is ordered to charge. If no chargers close by are available, the vehicle will accept a new container job. When the SoC reaches a level below 15% the vehicles can not accept any more jobs and are sent to be charged. At the charging location, all batteries are charged to full capacity. The progressive policy takes advantage of the idle status of chargers, increasing their utilisation. Furthermore, the policy may reduce the likelihood of the vehicle reaching the minimum SoC, which reduces the out-of-operation time of these vehicles.

4.1.4. Opportunity Charging

The work by Simpson, Asce, Thiessen, *et al.* [4] and Mohr, Kastner, and Jahn [5] introduces opportunity charging for battery-powered vehicles. The charging strategy is to implement opportunistic charging as part of the operational cycle. This strategy assumes a sufficient number of recharging stations are strategically placed throughout the terminal to provide quick and convenient energy replenishment. The equipment is charged for a couple of minutes, with high charging power, provides enough energy for up to 0.5-2 hours of operation, depending on charging power and battery capacity. The concept of the opportunity charging policy can be combined with fast-charging wireless charging. The work by [15] describes how inductive chargers, located at the quay and on RTGs, can be used to charge BTTs when operating in a terminal. During the operational cycle, the BTT operates as usual and is charged wireless during interchange operations. This ensures no loss in production, but requires expensive, energy-hungry, chargers to be installed at every RTG and QC transfer point.

5. Modelling

The models used in this research will be built in the simulation software TIMESQUARE, developed by Portwise. The RTG/TT discrete-event simulation model used by Portwise will serve as the basis for a model and is adapted to incorporate battery-powered terminal trucks and the charging of these vehicles.

5.1. RTG terminal model

Figure 3 shows a figure of an example RTG/TT model. The model shows a typical representation of an RTG terminal with many RTGs handling the containers in multiple yard modules. The model is a general representation of an RTG terminal with diesel-powered TTs. RTGs can move between the different modules when needed. Several QCs, depicted at the bottom of the figure, handle the different vessels docked at the quay and move containers between the BTTs and the vessels. In the upper left corner is where the gate is situated. It is here that the external trucks XTs delivering and picking up containers pass through. XTs exit the model again via the same gate. TTs use the same driving lanes as XTs and shuttle containers between the quay and the yard. The colour of the cabin distinguishes the two types of vehicles. The XT has a blue cabin, whereas the TT has a red cabin.

Figure 3. RTG terminal model in Timesquare

The terminal operations simulated are controlled by a central Terminal Operating System (TOS). This system manages the interaction between the different vehicles and infrastructure to simulate a real-life container terminal. The TOS manages the loading and unloading plan of the vessels and controls which (B)TT handles which container. It also controls the interaction between (B)TT and RTG. Each vehicle has its controls to simulate the driving and route handling. Finally, it also manages the charging orders for the BTTs. Following the implemented charging policy, it determines when BTTs can no longer accept container operations and are ordered to charge.

5.2. Battery-Powered Terminal Trucks

5.2.1. Energy Consumption

A functionality added to the model is the consumption and monitoring of the energy consumption of the BTTs, completing the RTG/BTT model. This will simulate the BTTs using electrical energy from their batteries and keep track of the SoC of the vehicles. The power required to operate the electrical motors in the BTTs differs during different driving states. As shown in the table, a BTT requires more power during acceleration whilst fully loaded and only uses a small amount of energy during a standstill. During the simulation at every timestep, the current power usage of the BTTs is determined and used to calculate the energy consumption during that timestep. Table 2a gives the range of engine power depending on different speeds and loads during acceleration and constant driving. The current power usage is calculated by linear interpolation for the current load and speed. At 0 m/s the BTTs are not driving but still use a small amount of energy to keep systems up and running. During braking some energy can be regenerated resulting in some recuperated energy. The power curve for this is given in Table 2b.

Speed(m/s)\Load(t)	0	30
0	1 kW	1 kW
8.4	150 kW	300 kW

(a) Aceleration and constant driving

Speed(m/s)\Load(t)	0	30
0	1 kW	1 kW
8.4	-30 kW	-60 kW

(b) Deceleration

Table 2. Engine Power tables

5.2.2. Charging stations

When the battery of the BTT needs to be recharged, this is done at a charging station. Charging is done either conductive or inductive. A charging station can house multiple charging lanes where BTTs can be charged. At a charging station the BTTs park for a certain amount of time whilst their battery is replenished. Charging is done linearly to a set amount of SoC. The charging time depends on the battery capacity of the vehicle and the charging capacity of the charging stations. These capacities are determined by charging strategy choices and differ between the different design alternatives. Whilst a BTT is charging its SoC is updated every timestep and logged.

Portwise had some functionalities of charging stations in some of its models. These were only used for battery-swapping AGVs and thus needed to be adapted to work with BTTs. The ability to charge via conductive or inductive charging was implemented

5.3. Charging Strategies

With the knowledge gathered during the literature study on the different charging strategies presented in section 4, charging strategies for specifically charging BTTs were inventoried or adapted. This resulted in several design alternatives that will be investigated. A design alternative comprises the combination of charging infrastructure type, location, and charging policy. Each design alternative has been implemented in the RTG/BTT model.

5.3.1. Out of Operations Charging (OOP)

The first design alternative uses a substantial number of wired chargers to charge the BTTs during downtime at the terminal, often at night. At the start of the simulation, all vehicles have a maximum SoC and will not need intermediate charging. The battery capacity of the BTTs is enough to complete a full 8-hour shift. The SoC of each BTT is still monitored. Figure 4 describes the control loop as performed by the TOS during operations. When the plan cycle is initiated it first checks which vehicle is available next from a list of all vehicles. A vehicle is only available if it currently not charging or not performing a container order. BTTs are assigned to perform container orders until the battery level reaches a critical SoC. For this charging strategy, this should never occur, but it is still included as a precaution. If a BTT were to accidentally reach a critical Soc is ordered to return to the depot and park there. It is no longer available to perform container orders.

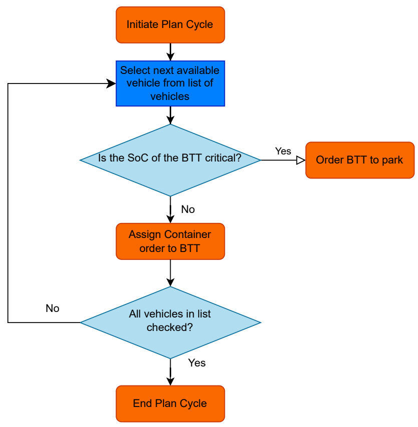

Figure 4. Control structure DA1

5.3.2. Centralised Fixed Threshold Charging (CFT)

The second design alternative uses several centrally located charging stations with a number of charging lanes per station to charge the BTTs during container terminal operations.

Figure 5 shows the control structure as used by the TOS for this design alternative. When a BTT reaches a fixed charging threshold it is no longer allowed to transport containers and is ordered to go in for a charge. The availability of the charging lanes is checked. If a charging lane is available at any of the charging stations the BTT is ordered to charge at that lane. If no lanes are available the BTTs are ordered to park at the charge stations. Once a charge lane becomes available it will be ordered to go in for a charge.

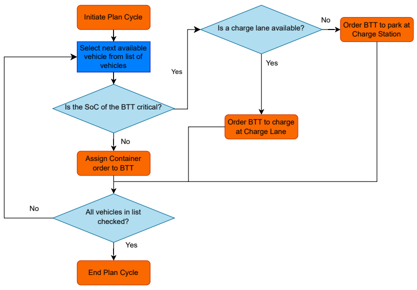

Figure 5. Control structure DA2

5.3.3. *Decentralised Fixed Threshold Charging (DFT)*

The third design alternative utilises charging stations with several charging lanes per station, spread throughout the terminal at strategic locations. Which has the advantage that driving time to a charging station could be less compared to centrally located charging stations.

Figure 6 shows the control structure as used by the TOS for this design alternative. When a BTT reaches a fixed charging threshold it is no longer allowed to transport containers and is ordered to go in for a charge. The availability of the different charging lanes is checked. If more than one charge lane is available, the charge lane closest to the BTT is selected. If no charge lanes are available the charge lane that becomes available first to the BTT is selected and the BTT is ordered to park at the charge station of this charge lane. When the charge lane becomes available the BTT is ordered to go charge.

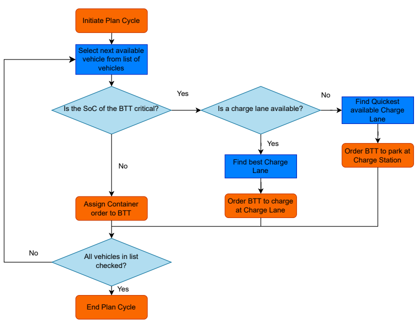

Figure 6. Control structure DA3

5.3.4. *Decentralised Pre-Emptive Charging (DPE)*

The fourth design alternative uses the same charging infrastructure as the previous charging strategy. The charging threshold for the fleet of BTTs is dynamic and continuously monitored based on the SoC of all BTTs in the fleet.

Figure 7 describes the control structure used by the TOS for this charging strategy. The average SoC of the entire fleet is continuously tracked, and the charging threshold adjusts accordingly. When the average SoC remains above 60%, the charge threshold is set at 20%. If the average SoC falls between 60% and 50%, the charge threshold linearly increases from 20% to 40%, prompting vehicles to initiate charging earlier. Should the average SoC drop below 50%, the charge threshold is maintained at 40%. This dynamic charging threshold ensures that more vehicles are preemptively sent for charging as the average SoC of the fleet decreases.

Unlike a fixed charge threshold, which could result in multiple vehicles reaching the threshold simultaneously, the dynamic approach staggers charging times. By dynamically adjusting charging based on the fleet's SoC, the system enhances the overall terminal efficiency and readiness of the BTTs.

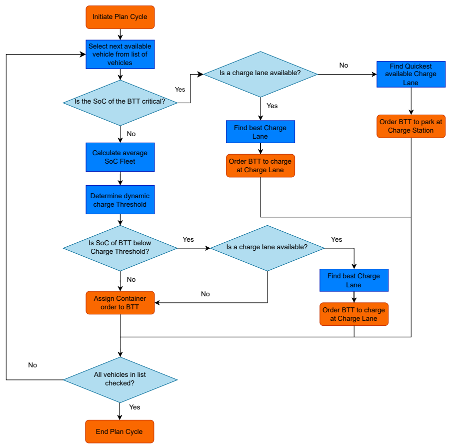

Figure 7. Control structure DA4

5.3.5. *Decentralised Opportunity Charging (DOP)*

The last design alternative uses high-powered inductive chargers at every RTG to charge the BTTs during the period it is alongside the RTG. This will ensure that no time is lost during container operations. The model simulates this by updating the SoC of the BTT by a certain amount every time it completes a transfer with an RTG (both pick-up and delivery). This amount is the average energy consumption per container moved in the terminal. This needs to be determined with a preliminary simulation. In this research, the average energy consumption per container measured during the testing of design alternative 1 will be used. To make sure no BTT depletes its battery too much, the SoC of all BTTs is still monitored. The TOS uses the same control structure as presented in Figure 4.

5.4. Verification and Validation

The models created for this thesis were verified using code reviews and tracing methods, and their validity was further assessed by examining the animations generated by the simulation software, in line with the approach described by Sargent [16]. Given the limited adoption of BTTs in container terminals, it was not possible to validate the models using real-world data. Instead, industry experts from Portwise reviewed the models and confirmed that they were representative of real-world conditions.

6. Experimental Setup

During all tests the general configuration of the RTG terminal and the (B)TTs is configured with values depicted in Table 3. These values are provided by Portwise and do not correspond to a specific RTG terminal.

Parameter	Value	Unit
Number of Storage yard blocks	32	-
Number of RTGs	32	-
Number of QCs	10	-
Quay Length	1200	m
Terminal Depth	300	m
Number of Vessels	3	-
External Trucks per hour	150	-

Table 3. Terminal configuration parameters

A set of experiments were conducted to test the performance of the different charging strategies in varying configurations and charger numbers compared to the benchmark of an RTG terminal with diesel-powered TTs. All experiment configurations are presented inTable 4.

Exp.	DA	#(B)TT	Battery (kWh)	Charge cap (kW)	#Charge Lanes
1	Diesel	40	-	-	-
2		50	-	-	-
3		60	-	-	-
4	OOP	50	350	-	-
5	CFT	60	150	150	10
6		60	150	150	12
7		60	150	150	14
8		60	150	150	16
9	DFT	60	150	150	10
10		60	150	150	12
11		60	150	150	14
12		60	150	150	16
13	DPE	60	150	150	10
14		60	150	150	12
15		60	150	150	14
16		60	150	150	16
17	DOP	50	25	500	32

Table 4. Experimental configurations

Each experiment includes 25 replications, with a fixed load plan applied consistently across all experiments. This approach ensures that the QCs are consistently presented with the same mix and type of containers in each experiment, making the comparison between charging strategies more reliable and less influenced by variability in the load plan. While the QCs are exposed to the same possibilities within the load plan, they may not handle the same containers in every replication. Each replication executes a portion of the load plan within a single simulation run. Furthermore, each specific replication within any experiment starts at the same point in the load plan. For example, replication 4 in experiment 3 will use the same part of the load plan as replication 4 in experiments 5, 6, 7, and so on. The load plan is divided into 25 sections, resulting in 25 replications per experiment.

To test the performance of the different charging strategies the Key Performance Indicator (KPI) of QC productivity is used. This number indicates the average number of containers moved per QC per hour. It is often the most important performance indicator for a terminal and critical to ensure that a strategy can perform at a required performance level. Furthermore, it serves as a means of comparing different strategies.

Although QC productivity is of great importance the costs associated with this performance level by a certain strategy can not be overlooked. Acquiring extra vehicles or chargers could ultimately contribute to high QC productivity but if this results in enormous investment cost in extra equipment it is not desirable. To quantitatively compare the cost of the different charging strategies some cost estimations concerning vehicles and charging infrastructure have been made using publicly available sources and expert knowledge by Portwise employees [17] [18].

Equipment/Charging Infrastructure	Cost
Diesel Terminal Truck	€ 120,000.00
Battery-Powered Terminal Truck (25 kW)	€ 190,000.00
Battery-Powered Terminal Truck (150 kW)	€ 250,000.00
Battery-Powered Terminal Truck (350 kW)	€ 350,000.00
Charger 50 kW	€ 45,000.00
Charger 150 kW	€ 90,000.00
Charger 500 kW	€ 500,000.00

Table 5. Cost estimations Equipment and Charging infrastructure

Operating cost per operational hour		
	Diesel	Battery
Energy consumption (l/h)/(kWh/h)	10	20
Fuel/Energy (€/l)/(€/kWh)	€ 1.60	€ 0.20
Maintenance cost per operating hour	€ 13.60	€ 9.50
Total operating cost per operating hour	**€ 29.60**	**€ 13.50**

Table 6. Cost estimation Operational Cost

7. Results

7.1. Results all experiments

Figure 8 and Table 7 provides an overview of the average QC productivity for each of the tested configurations. When comparing the average productivity across different charging strategies, there is little statistically significant difference, except for CFT 10 CL which performs significantly poorly than most alternatives and DPE 16 CL, which outperforms most other alternatives. Although the differences are mostly not statistically significant, a slight improvement in productivity is observed between Design Alternatives 2 CFT, 3 DFT, and 4 DPE, with decentralised charging using a dynamic charge threshold performing best. Design Alternative 1 OOP and 5 DOP strategies perform similarly to the 50 TT benchmark. This is as expected because the charging of BTTs does not influence the QC productivity.

Several configurations meet or exceed the target average QC productivity of the benchmark 50 TT of 25.73 bx/hr, which was set as a target performance with only Design Alternative 2 - 10 CL and Design Alternative 3 - 10 CL falling short with statistical significance. All charging strategies show statistically significant improvements over the 40 TT benchmark, but none reach the performance level of the 60 TT benchmark.

Figure 9 gives the cost estimation for each of the tested configurations. These cost estimations are made for the entire lifetime of the fleet of (B)TTs set at 10 years. The operating cost of the fleet of BTTs for each strategy is calculated with the estimated operational hours per year, calculated with the average peak QC productivity and total volume of containers expected to move through the RTG terminal per year. With the terminal parameters as presented in Table 3, the expected throughput was estimated by Portwise employees to be 900,000 containers per year.

Due to the high operating cost, resulting from high fuel and maintenance costs, the benchmark diesel configurations are the most expensive. Despite significant BTT and charger investment costs the OOP strategy is the cheapest alternative. The equipment investment cost of the CFT, DFT and DPE strategies are similar to the decentralised alternatives costing slightly more in terms of cost for charging infrastructure (cost included for extra electrical connections). The operational cost of the different configurations with the same BTT fleet size decreases with increasing QC productivity. This is due to the same amount of vehicles operating more efficiently. Regarding the DOP strategy, it is clear that the investment in high-capacity wireless chargers for each RTG leads to substantial infrastructure costs. Combined with the investment required for the fleet of BTTs, this accounts for nearly half of the total cost. Overall the total cost of the DOP strategy is the highest of all the battery-powered RTG terminal configurations.

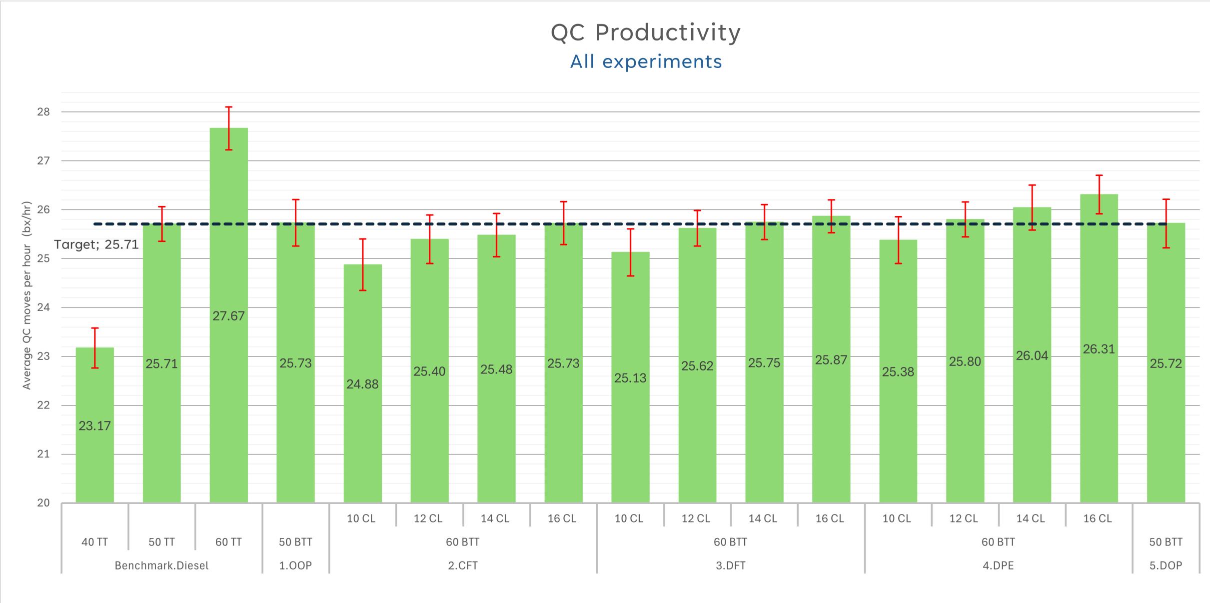

Figure 8. QC productivity all experiments

	QC productivity (box/hr)																
DA	Diesel			OOP	CFT				DFT				DPE				DOP
Experiment	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Average	23.17	25.71	27.67	25.73	24.88	25.40	25.48	25.73	25.13	25.62	25.75	25.87	25.38	25.80	26.04	26.31	25.72
95% Confidence	±0.41	±0.35	±0.44	±0.48	±0.53	±0.50	±0.44	±0.44	±0.48	±0.37	±0.36	±0.34	±0.48	±0.36	±0.46	±0.39	±0.50

Table 7. QC Productivity all experiments

Figure 9. Cost estimation all experiments

			QC productivity Difference (box/hr)													
			OOP	**CFT**				**DFT**				**DPE**				**DOP**
				10 CL	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	
		QCR	**25.73**	**24.88**	**25.4**	**25.48**	**25.73**	**25.13**	**25.62**	**25.75**	**25.87**	**25.38**	**25.8**	**26.04**	**26.31**	**25.72**
Diesel	*40 TT*	**23.17**	2.56	1.71	2.23	2.31	2.56	1.96	2.45	2.58	2.7	2.21	2.63	2.87	3.14	2.55
	50 TT	**25.71**	0.02	-0.83	-0.31	-0.23	0.02	-0.58	-0.09	0.04	0.16	-0.33	0.09	0.33	0.6	0.01
	60 TT	**27.67**	-1.94	-2.79	-2.27	-2.19	-1.94	-2.54	-2.05	-1.92	-1.8	-2.29	-1.87	-1.63	-1.36	-1.95

Table 8. QC productivity versus Benchmark

		QC productivity paired T-Test P-values												
		OOP	**CFT**				**DFT**				**DPE**				**DOP**
			10 CL	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	
Diesel	*40 TT*	1.18E-12	9.69E-09	3.02E-11	1.11E-11	3.45E-13	1.88E-09	6.62E-13	2.10E-12	1.04E-13	2.17E-09	1.39E-12	1.03E-14	1.15E-14	9.31E-13
	50 TT	0.91	0.00	0.16	0.22	0.95	0.02	0.65	0.84	0.38	0.18	0.66	0.16	0.01	0.97
	60 TT	4.47E-08	5.31E-13	2.73E-09	1.38E-09	1.12E-08	7.21E-10	1.21E-08	2.06E-10	7.36E-08	2.60E-08	2.87E-08	4.82E-07	9.59E-07	4.48E-08

Table 9. Paired T-Test P-Values

7.2. Productivity versus Diesel Benchmark

A comparison of the productivity has been made between the different charging strategies and the diesel-powered benchmarks. Table 8 presents the differences in QC productivity between the different charging strategies and the benchmark diesel options. A paired t-test was performed to test statistical significance. The results are shown in Table 9. P-values below 0.05 indicate a statistically significant difference in QC productivity, while P-values above 0.95 suggest a statistically significant comparable average QC productivity. The former is crucial for demonstrating a significant decrease or improvement in performance, while the latter indicates a strong comparable performance. For P-values in between the comparison is inconclusive. Based on the results in the tables, it is evident that each charging strategy performs significantly better than the 40 TT diesel benchmark but falls significantly short of the 60 TT benchmark. Only looking at the comparison with the 50 diesel TTs, several observations can be made. The QC productivity of the DOP strategy, as well as the CFT - 16 CL configuration, is statistically comparable to the 50 TT benchmark. The QC productivity of the OOP strategy is strongly comparable to that of the 50 TT diesel benchmark although it falls slightly short of being statistically significant with a P-value of 0.91. The CFT and DFT strategies with 10 charging lanes perform statistically worse than the 50 TT benchmark. The DPE - 16 CL configuration is the only one that statistically outperforms the 50 TT diesel benchmark. For all other charging strategy configurations, there is no statistical evidence to conclude whether their performance is worse, equal to, or better than that of the 50 TT diesel benchmark.

8. Conclusion

This research aimed to test different charging strategies for battery-powered container terminal trucks with the use of a large-scale terminal operation simulation. Using the simulations, the research investigated the influence of different charging strategies for battery-powered terminal trucks on the terminal performance and cost of an RTG terminal compared to benchmark diesel-powered operations.

This research demonstrates that the choice of charging strategy for battery-powered terminal trucks significantly influences both the productivity and cost of RTG-based container terminals.

When employing strategies such as Out of Operation and Decentralised Opportunity Charging, BTT charging does not negatively impact terminal productivity. The performance metrics for these strategies are statistically comparable to those of terminals utilising the same number of diesel-powered terminal trucks.

However, charging during container handling operations necessitates the deployment of additional vehicles due to the downtime required for charging, leading to the need for supplementary vehicles to maintain performance similar to a smaller fleet of diesel-powered terminal trucks. The study also highlights that while the location of charging stations provides a slight, though not statistically significant, improvement in QC productivity, a limited number of charging lanes adversely affects QC productivity.

The implementation of a decentralised pre-emptive charging strategy with a dynamic charge threshold emerges as a promising strategy, as it minimises charge waiting times and BTT idle periods, thus enhancing QC productivity whilst also stabilising charge lane utilisation. Conversely, central charging with a fixed threshold and limited charging lanes strongly impairs QC productivity. Increasing the number of available charge lanes decreases this.

Despite the higher upfront vehicle and infrastructure investments required, battery-powered terminal trucks offer the advantage of lower operational costs over their lifetime compared to diesel alternatives. Particularly, out of operations charging proves to be the most cost-effective strategy, provided the terminal has sufficient downtime to accommodate simultaneous vehicle charging. On the other hand, decentralised opportunity charging, while offering high flexibility, incurs the highest costs, primarily due to the substantial investment needed for high-capacity wireless charging infrastructure.

Taking both QC productivity and total cost into consideration, the study concludes that decentralised pre-emptive charging with a large number of charge lanes is the optimal strategy. This approach not only outperforms the 50 TT diesel benchmark in terms of QC productivity but also achieves the lowest total cost by maximising operational efficiency and minimising operating expenses. Thus, for RTG-based terminals aiming to balance productivity with cost-effectiveness, this strategy stands out as the most viable and advantageous solution.

9. Recommendations

Further research is recommended to evaluate the impact of charging strategies on the performance of battery-powered terminal trucks.

1. Alternative Terminal Layouts: Simulate larger terminal layouts to test the effect of travel distance to charging stations on QC productivity and BTT status. Testing in larger terminals may reveal more significant effects on terminal performance.

2. Testing Charging Strategies in Real-life RTG Terminal Setups: Research charging strategies within an actual RTG terminal setup, using a specific terminal with known energy consumption, cost estimations for battery-powered terminal trucks (BTTs), and realistic fleet size. This approach will allow for a more accurate assessment of the true impact of switching to battery-powered trucks on a large scale.

3. Effect of Battery Size and Charger Capacity: Investigate the relationship between battery size, charger capacity, and the balance between charge time and operational time for BTTs. Understanding how these factors interact will be crucial in optimising the charging process and ensuring that BTTs can operate efficiently without excessive downtime.

4. Development and Testing of Other Charging Strategies:

Linking Charging and Work Demand: Develop and test strategies that adjust charging based on work demand at the quay. For example, during slow periods in a shift, more charging can be scheduled, while during busy peaks, less charging would be allowed.

Opportunity Charging with Dynamic Recharging: Explore the concept of opportunity charging, where the amount of battery replenishment is dynamically adjusted to match the energy consumption needed for the next container handling operation of the BTT. This strategy could lead to more effective use of available charging time and reduce the likelihood of BTTs being under or overcharged.

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B

Appendix

B.1. Results all experiments

	QC productivity (box/hr)																
	Diesel			OOP	CFT				DFT				DPE				DOP
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	22.44	24.96	26.36	25.61	22.27	25.26	26.04	25.33	24.84	25.77	25.27	25.66	24.07	26.07	25.01	26.66	24.96
2	23.64	26.06	28.10	26.09	26.03	26.10	25.79	25.71	23.70	25.36	26.89	24.71	24.73	24.24	26.54	26.17	26.16
3	21.86	25.01	26.94	24.56	25.80	23.54	23.87	22.30	24.41	25.13	25.71	24.96	25.06	25.94	25.93	25.50	24.51
4	24.80	26.41	26.99	27.24	25.94	27.40	26.39	26.83	27.21	28.03	25.21	27.13	27.53	26.43	27.81	28.20	27.44
5	23.61	25.29	27.86	25.17	24.96	22.89	22.87	25.74	26.30	26.07	25.17	26.19	24.00	24.99	26.61	25.64	26.71
6	23.30	24.81	25.60	25.44	23.87	25.21	25.23	25.79	25.70	24.96	24.43	25.31	26.07	25.27	26.13	25.97	24.20
7	23.14	26.16	27.80	26.11	24.67	25.21	24.49	26.06	23.70	23.91	26.03	25.14	24.93	27.20	26.60	25.01	25.33
8	22.43	25.74	27.40	26.76	24.30	24.96	26.23	26.53	23.39	26.26	24.34	26.03	25.11	25.73	26.47	25.71	24.97
9	23.20	26.56	28.61	26.61	25.24	26.99	26.09	25.49	27.29	24.94	25.06	24.94	25.76	26.50	26.67	26.93	26.11
10	24.43	27.13	28.59	26.64	27.04	27.51	25.99	26.86	26.44	27.13	27.07	27.54	26.01	26.94	26.64	28.69	27.43
11	25.20	25.47	28.16	25.89	25.77	26.57	26.67	26.59	25.20	26.34	26.61	26.83	24.84	26.63	27.04	26.59	27.63
12	23.40	26.24	27.83	24.39	24.54	25.07	25.61	25.36	24.09	24.44	25.97	25.63	26.14	25.09	25.09	26.04	24.04
13	23.17	24.83	28.89	25.94	25.80	24.67	25.54	26.23	25.77	25.64	25.14	25.51	25.63	27.16	26.46	27.07	24.77
14	23.57	27.20	28.34	24.99	26.24	26.86	26.71	25.43	24.76	25.90	26.17	26.40	26.04	25.96	25.07	26.50	25.37
15	22.84	26.19	26.90	24.73	22.99	24.34	24.74	24.57	23.74	25.56	26.11	25.93	23.26	25.07	23.70	25.96	24.83
16	22.56	26.19	28.36	25.83	25.27	25.01	26.23	25.70	24.89	25.71	25.86	26.23	24.99	25.51	26.01	26.56	26.10
17	21.41	24.20	27.26	22.23	23.94	24.79	23.81	25.34	24.47	25.24	25.43	26.73	26.89	24.61	23.24	25.59	25.67
18	24.87	26.74	30.00	27.81	26.71	27.19	27.21	27.87	27.21	26.77	27.27	26.64	27.63	27.16	27.91	27.91	28.37
19	23.86	26.54	28.99	26.81	26.10	25.26	26.01	25.67	25.90	26.39	26.31	27.16	26.31	24.86	27.00	25.81	26.34
20	22.29	23.84	27.37	24.60	24.91	26.20	24.46	26.50	23.54	24.94	26.10	24.56	24.23	25.74	26.16	27.21	25.34
21	22.34	25.94	27.00	25.11	24.37	24.79	25.87	26.19	25.34	25.83	26.74	25.51	26.46	26.10	26.71	25.49	26.30
22	23.90	25.27	26.09	26.54	24.84	25.23	26.06	26.03	25.30	25.14	25.40	26.01	26.31	26.53	26.33	25.04	25.80
23	22.47	25.20	27.37	26.39	24.57	24.19	25.10	25.76	24.24	24.74	26.01	25.23	23.90	24.64	25.71	25.73	26.43
24	21.74	25.21	26.00	25.30	22.06	24.17	23.90	23.81	25.13	25.33	23.67	25.71	24.53	24.96	24.56	25.31	24.51
25	22.77	25.56	28.90	26.57	23.63	25.56	26.10	25.49	25.60	24.99	25.69	25.01	24.07	25.76	25.67	26.54	23.67
Average	23.17	25.71	27.67	25.73	24.88	25.40	25.48	25.73	25.13	25.62	25.75	25.87	25.38	25.80	26.04	26.31	25.72
95% Con	$\pm$0.41	$\pm$0.35	$\pm$0.44	$\pm$0.48	$\pm$0.53	$\pm$0.50	$\pm$0.44	$\pm$0.44	$\pm$0.48	$\pm$0.37	$\pm$0.36	$\pm$0.34	$\pm$0.48	$\pm$0.36	$\pm$0.46	$\pm$0.39	$\pm$0.50

Table B.1: QC productivity all Replications

			QC productivity Difference (box/hr)																
			Diesel			**OOP**	**CFT**				**DFT**				**DPE**				**DOP**
			40 TT	*50 TT*	*60 TT*		*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	
		QCR	**23.17**	**25.71**	**27.67**	**25.73**	**24.88**	**25.40**	**25.48**	**25.73**	**25.13**	**25.62**	**25.75**	**25.87**	**25.38**	**25.8**	**26.04**	**26.31**	**25.72**
Diesel	*40 TT*	**23.17**	-	2.54	4.5	2.56	1.71	2.23	2.31	2.56	1.96	2.45	2.58	2.7	2.21	2.63	2.87	3.14	2.55
	50 TT	**25.71**	-	-	1.96	0.02	-0.83	-0.31	-0.23	0.02	-0.58	-0.09	0.04	0.16	-0.33	0.09	0.33	0.60	0.01
	60 TT	**27.67**	-	-	-	-1.94	-2.79	-2.27	-2.19	-1.94	-2.54	-2.05	-1.92	-1.80	-2.29	-1.87	-1.63	-1.36	-1.95
OOP		**25.73**	-	-	-	-	-0.85	-0.33	-0.25	0	-0.60	-0.11	0.02	0.14	-0.35	0.07	0.31	0.58	-0.01
CFT	*10 CL*	**24.88**	-	-	-	-	-	0.52	0.6	0.85	0.25	0.74	0.87	0.99	0.50	0.92	1.16	1.43	0.84
	12 CL	**25.4**	-	-	-	-	-	-	0.08	0.33	-0.27	0.22	0.35	0.47	-0.02	0.40	0.64	0.91	0.32
	14 CL	**25.48**	-	-	-	-	-	-	-	0.25	-0.35	0.14	0.27	0.39	-0.10	0.32	0.56	0.83	0.24
	16 CL	**25.73**	-	-	-	-	-	-	-	-	-0.60	-0.11	0.02	0.14	-0.35	0.07	0.31	0.58	-0.01
DFT	*10 CL*	**25.13**	-	-	-	-	-	-	-	-	-	0.49	0.62	0.74	0.25	0.67	0.91	1.18	0.59
	12 CL	**25.62**	-	-	-	-	-	-	-	-	-	-	0.13	0.25	-0.24	0.18	0.42	0.69	0.10
	14 CL	**25.75**	-	-	-	-	-	-	-	-	-	-	-	0.12	-0.37	0.05	0.29	0.56	-0.03
	16 CL	**25.87**	-	-	-	-	-	-	-	-	-	-	-	-	-0.49	-0.07	0.17	0.44	-0.15
DPE	*10 CL*	**25.38**	-	-	-	-	-	-	-	-	-	-	-	-	-	0.42	0.66	0.93	0.34
	12 CL	**25.8**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.24	0.51	-0.08
	14 CL	**26.04**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.27	-0.32
	16 CL	**26.31**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-0.59
DOP		**25.72**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table B.2: QC productivity Difference All experiments

		P-values Paired T-Test																
		Diesel			**OOP**	**CFT**				**DFT**				**DPE**				**DOP**
		40 TT	*50 TT*	*60 TT*		*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	*10 CL*	*12 CL*	*14 CL*	*16 CL*	
Diesel	*40 TT*	-	2.47E-13	1.14E-16	1.18E-12	9.69E-09	3.02E-11	1.11E-11	3.45E-13	1.88E-09	6.62E-13	2.10E-12	1.04E-13	2.17E-09	1.39E-12	1.03E-14	1.15E-14	9.31E-13
	50 TT	-	-	0.00	9.06E-01	1.33E-03	1.56E-01	2.22E-01	9.47E-01	2.16E-02	6.46E-01	8.42E-01	3.84E-01	1.81E-01	6.63E-01	1.63E-01	8.16E-03	9.65E-01
	60 TT	-	-	-	4.47E-08	5.31E-13	2.73E-09	1.38E-09	1.12E-08	7.21E-10	1.21E-08	2.06E-10	7.36E-08	2.60E-08	2.87E-08	4.82E-07	9.59E-07	4.48E-08
OOP		-	-	-	-	0.00	0.18	0.20	0.97	0.02	0.62	0.96	0.61	0.25	0.75	0.06	0.02	0.96
CFT	*10 CL*	-	-	-	-	-	0.04	0.03	0.00	0.37	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
	12 CL	-	-	-	-	-	-	0.63	0.12	0.31	0.34	0.15	0.06	0.94	0.08	0.02	0.00	0.20
	14 CL	-	-	-	-	-	-	-	0.23	0.19	0.52	0.24	0.10	0.68	0.14	0.02	0.00	0.37
	16 CL	-	-	-	-	-	-	-	-	0.03	0.62	0.92	0.51	0.17	0.72	0.12	0.01	0.98
DFT	*10 CL*	-	-	-	-	-	-	-	-	-	0.02	0.04	0.00	0.28	0.01	0.00	0.00	0.02
	12 CL	-	-	-	-	-	-	-	-	-	-	0.58	0.04	0.30	0.41	0.06	0.00	0.59
	14 CL	-	-	-	-	-	-	-	-	-	-	-	0.57	0.18	0.80	0.23	0.01	0.90
	16 CL	-	-	-	-	-	-	-	-	-	-	-	-	0.03	0.77	0.50	0.04	0.46
DPE	*10 CL*	-	-	-	-	-	-	-	-	-	-	-	-	-	0.09	0.02	0.00	0.20
	12 CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.24	0.01	0.75
	14 CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.25	0.13
	16 CL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01
DOP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table B.3: P-values Paired T-Test All experiments

B.2. Comparative Analysis CFT, DFT, DPE

To investigate the overall effect of charge station location and the use of a dynamic charge threshold the average QC productivity of the CFT, DFT and DPE strategies is investigated. Table B.4 shows the difference in QC productivity between the strategies and Table B.5 provides the analysis of the statistical significance of these differences. It can be observed that a small improvement in productivity is observed between DFT and CFT, although barely not statistically significant. The DPE strategy performs statistically significant better than the CFT and DFT strategies.

QC productivity Difference (box/hr)				
		CFT	DFT	DPE
	QCR	**25.37**	**25.59**	**25.89**
CFT	**25.37**	-	0.22	0.52
DFT	**25.59**		-	0.30
DPE	**25.89**			-

Table B.4: Average QC productivity Difference CFT, DFT, DPE

P-values paired T-Test			
	CFT	DFT	DPE
CFT	-	0.06	0.00
DFT		-	0.01
DPE			-

Table B.5: P-values Paired T-Test CFT, DFT, DPE