Evaluating the operational and financial feasibility of battery-electric AGVs at brownfield container terminals

A design study at ECT Delta Terminal

I. Bouhannouche 4307496

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by

I. Bouhannouche 4307496

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Student name:	Ilias Bouhannouche	
Student number:	4307496	
Report number:	2019.TIL.8315	
E-mail:	iliasb.1995@gmail.com	
Phone:	+316 4916 3073	
Project duration:	May 28, 2018 – February 7, 2019	
Thesis committee:	Prof. dr. R. R. Negenborn,	TU Delft, chairman
	Dr. J. M. Vleugel,	TU Delft, daily supervisor
	Dr. ir. Y. Pang,	TU Delft, daily supervisor
	ing. T. P. Middelburg,	Europe Container Terminals, external supervisor

This thesis is confidential and cannot be made public until February 7, 2024.

Preface

This report is the result of a seven-months research conducted at Europe Container Terminals (ECT), one of the largest deep sea container terminal operators in the world and the world's first in implementing Automated Guided Vehicles (AGV) in its container transshipment process. As during my Master Transport, Infrastructure and Logistics I developed a great interest in the simulation of transport systems, I did not hesitate to contact ECT after having organized a seminar there in June 2017. Main topic was the transition of their diesel AGVs to a battery-electric fleet..a thesis subject was born. I can certainly say that I have learned a lot from this project, of which the most important one is *scoping*.

First and foremost, I would like to thank my daily supervisors Dr. Jaap Vleugel and Dr. ir. Yusong Pang for their extensive supervision, critical eye and new insights which have surely led to this final Thesis report. Their patience, support and open offices during my graduation period really helped me in making progress with this large project. Also, I would like to thank ing. Paul Middelburg from ECT for his external supervision and for bringing me in contact with the right experts within ECT; it has been a great time for me working at the Delta Terminal mainly due to his, and all ECT employees', enthusiasm and approachability. Finally, I would like to thank Prof. dr. Rudy Negenborn for accepting me as his graduate student and for his critical eye and advice during the official progress meetings; his key contributions during these meetings have really shaped this project.

Besides my Thesis committee members, who contributed most to this project, I would also like to thank Arie Vroegindeweij and Alex Stevenson from ECT for providing me all the data I needed to perform this Thesis research. A special thanks to Arie for always making time to listen to the new insights I gained. Also, many thanks to Joris Obdam from ECT for keeping the scientific value of this research in mind. From the companies VDL and Heliox, I would like to thank Karel Smits, Jeroen van Herk and Bob Bouhuijs for their time and valuable insights regarding battery-electric AGVs.

A special thanks to my mother and father for their patience and endless mental support during this Thesis research. All praise to God for this invaluable gift.

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Executive summary

Background and research questions

Brownfield container terminals are currently deploying diesel-powered Automated Guided Vehicles only for 24/7 container transport between the quay cranes at water side and the stacking cranes at land side. As studied by Van Duin and Geerlings (2011), diesel AGVs pollute by far the most carbon dioxide when compared to other equipment at brownfield container terminals. Looking at the trends in formal legislation and market developments towards more sustainability due to increasing pressure on governments and the industry, these diesel AGVs are most likely to become outdated and taken on first in terminal's environmental policy and its corresponding AGV replacement program. In order to anticipate on future regulations, brownfield container terminals are conducting research on battery-electric AGVs, an emerging, zero-emission alternative to diesel AGVs. While battery-electric AGVs are environmentally friendly and thus appear to be a promising alternative for the future, the limited driving range and significantly longer replenishment times of the batteries compared to the current diesel AGVs' fuel tanks raises questions about the operational feasibility of deploying electric vehicles, especially in transport systems running 24 hours a day. Next to operational concerns, battery-electric AGVs also require higher investment costs in both vehicles and charging infrastructure when compared to diesel AGVs. Although electric propulsion is expected to result in lower operational costs due to the reduction in fueling and maintenance costs, brownfield terminal operators do not know if these potential fuel and maintenance savings over an electric AGV's lifetime outweigh the higher initial investment costs in batteries and charging infrastructure. This lack of knowledge on the operational and financial feasibility of battery-electric AGVs compared to their current diesel AGV fleet has created a bottleneck for brownfield terminal operators to make a well funded decision whether or not to purchase battery-electric AGVs for their next AGV replacement program.

From literature, a clear knowledge gap is observable regarding the operational and financial feasibility of implementing battery-electric AGVs at brownfield container terminals. Therefore, the aim of this study was to fill this knowledge gap in order to contribute to solving the future challenge for brownfield terminal operators regarding deploying battery-electric AGVs for their quay-stack transport. Taking the northern side (DDN) of the ECT Delta Terminal, the largest deep sea container terminal of Europe, as a research object, this study's main research question was:

Is it operationally and financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?

In order to answer the main research question, several subquestions have been formulated:

1. How are diesel AGVs currently operated during daily transport operations at the Delta Terminal and how is tanking fitted into this process?
2. Where in the AGV operational process occur opportunities for battery charging?
3. Which design of the AGV charging process can be used for further evaluation based on brownfield terminal operator's requirements and constraints?
4. How does the design influence the operational performance when compared to diesel AGVs?
5. To what extent is the design financially feasible when compared to diesel AGVs?

Research methodologies and results

By using an adapted version of the systems engineering approach of Sage and Rouse (2009) as main research approach, three phases were sequentially traversed in order to answer the formulated research questions:

1. *Research object analysis*, in which the current state in container transport operations were analyzed. By operationalizing the AGV operational process, the most promising moments and locations for battery charging were obtained and subsequently used as input into the design phase.

2. *Development of alternative designs and selection*, in which functional designs of the AGV charging process were generated by means of a morphological chart. Based on predefined design requirements and constraints from the perspective of the terminal operator, a selection was made from the list of developed alternatives.
3. *Development of tests and evaluating the selected alternative*, in which the selected design was evaluated on its operational and financial feasibility by means of discrete event simulation and a total costs of ownership analysis.

1. Research object analysis

This study considers the water side of the DDN only; looking at Figure 1, encompassing the area in between the quay (bottom side) and the stack (top side). AGVs drive within this area in a grid structure, i.e. rectangularly, from the quay cranes (QC) to the automated stacking cranes (ASC) and vice versa with either a container on top or empty. AGVs can either perform a discharge or loading trip: when discharging, an AGV first drives empty to a QC (black line in Figure 1), where it loads a container on top, after which the AGV drives loaded to the corresponding ASC Transfer Point (TP) to unload its container (green line in Figure 1). When performing a loading trip, the AGV drives empty to an ASC TP, gets a container on top and then drives loaded to the destination QC, where its container is being loaded onto the ship. Finally, the current diesel AGVs only go tanking in case a threshold value has been reached and under the condition that the tanking process does not disturb the operational process.

Figure 1: AGV movements during a discharge trip in black and green and during tanking in red

By analyzing AGV driving data, for which the results are depicted in Figure 2, it was concluded that most opportunities for future battery charging occur at the ASC TPs and when queuing in the QC lane; at the ASC TPs both waiting and idle times could effectively be used for battery charging while in the QC lane only waiting times for (un)loading containers could be used for charging.

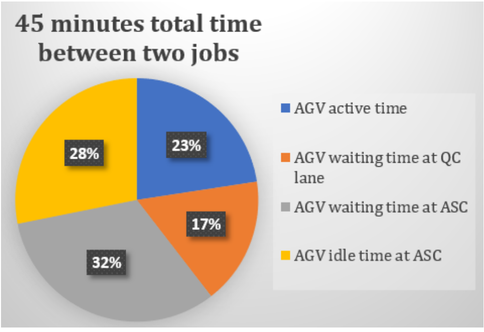


Figure 2: Total AGV time distribution in active, waiting and idle time

2. Development of alternative designs and selection

By means of a stakeholder analysis, it was found that brownfield terminal operators' logistical and financial departments are not triggered yet to cooperate in the acquisition of battery-electric AGVs due to the unknown impact of the battery charging process on their operations and finance. Scoping the design towards the future battery-electric AGV charging process only, this study's main design requirements are:

1. Incorporating the AGV charging process into the operational process should lead to equal operational performance compared to the current diesel AGV fleet

2. Implementing a battery-electric AGV fleet and its charging process should lead to equal or lower total costs of ownership compared to the current diesel AGV fleet

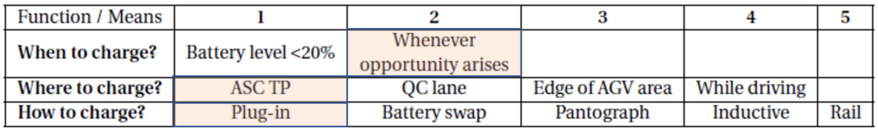
These requirements are operationalized into measurable quantities, i.e. criteria:
Operational criteria
Criterion 1: Vessel turnaround times in hours/vessel
Criterion 2: QC-AGV interaction in % of QC moves waiting for AGVs
Criterion 3: QC productivity in moves/hour/QC

Financial criteria
Criterion 1: Capital expenditures of infrastructure and AGVs in €
Criterion 2: Maintenance expenditures of infrastructure and AGVs over a predefined time horizon in €
Criterion 3: Fueling expenditures of AGVs over a predefined time horizon in €
Criterion 4: Terminal downtime expenditures over a predefined time horizon in €

Furthermore, the constraints with which AGV charging designs must comply are:

1. the AGV charging process shall never hinder QC operations
2. the charging technique used shall not cause damage to other terminal equipment and communication systems
3. the charging infrastructure shall fit within the current terminal layout
4. the charging technique used shall be available on the market

By functionally decomposing the AGV charging process into *when*, *where* and *how* to charge, alternatives have been trawled for each of these system functions into a morphological chart (see Figure 3). By combining alternatives over the system functions, a complete AGV charging process design is generated. By evaluating all designs on the predefined requirements and constraints, **opportunity plug-in charging at the ASC TPs** turned out to be the most promising AGV charging process design and is therefore selected for further evaluation on its operational and financial feasibility by means of simulation and a total costs of ownership analysis.



Function / Means	1	2	3	4	5
When to charge?	Battery level <20%	Whenever opportunity arises			
Where to charge?	ASC TP	QC lane	Edge of AGV area	While driving	
How to charge?	Plug-in	Battery swap	Pantograph	Inductive	Rail

Figure 3: Morphological chart with the selected design of the AGV charging process: opportunity plug-in charging at the ASC TPs

3. Development of tests and evaluating the selected alternative

Evaluating the operational feasibility
For the assessment of the transport performance, the operational criteria of the previous research phase have been used. As the main objective of this phase is to find out if electric charging is operationally feasible at brownfield terminals in general and at the ECT Delta Terminal in particular, variables influencing the operational performance of electric vehicles have been consequently looked up in literature. From this literature research, the *number of AGVs*, *battery capacity*, *charging power* and *number of chargers* turned out to be decisive for the determination of the operational performance of electric AGVs. The selected AGV charging design of the previous subquestion, opportunity plug-in charging at the ASC TPs, has consequently been experimented with by varying the above mentioned variables on a predefined range by means of discrete event simulation. The results of the simulation experiments indicate that the number of AGVs, charging power and number of chargers have a significant effect on the operational performance of deep sea container terminals. For the DDN, regarding the number of AGVs a convex relation with terminal operational KPIs is observed which flattens at 80 AGVs; from this point marginal improvement in turnaround times and terminal productivity is observed. Looking at differences in battery capacities, for the DDN no increase in terminal performance is perceived when increasing the battery size; 60 kWh batteries turn out to perform equally effective as 220 kWh batteries. Apparently, the idle time in between two jobs, roughly 15 minutes, is enough to charge

the AGV to a sufficient battery level, as is confirmed by the average charging time of 11 minutes. Moreover, when looking at the required charging power and number of chargers, 300 kW and 6 chargers prove to suffice in order to avoid deterioration in terminal performance.

From the experiment results, 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 charging spots turned out to perform operationally equal to the current diesel AGV fleet. By having conducted a future state analysis on this design configuration, in which current container arrivals have been sequentially increased with 20% and 40% to assess the robustness of a battery-electric AGV fleet, it was observed that battery-electric AGVs opportunity plug-in charged at the ASC TPs prove to be operationally resilient for future growth in container transshipment.

Evaluating the financial feasibility

Using a time horizon of 15 years, a fully battery-electric AGV fleet has been financially compared to the current diesel AGV fleet. Therefore, a two stage experimental analysis has been conducted: Therefore, a two stage experimental analysis has been conducted: in the first stage, similar to the operational evaluation, it is experimented with the number of AGVs, battery capacity, charging power and number of chargers in order to determine which design configuration results in the lowest cost difference with diesel AGVs whilst ensuring operational feasibility. The second stage subsequently tested this most promising design configuration by varying with the diesel, electricity and battery price levels in order to determine under what conditions a battery-electric AGV fleet opportunity plug-in charged at the ASC TPs is financially feasible when compared to the current state with diesel AGVs. For the first stage, the configuration that turned out to be most cost effective at the DDN side of the Delta Terminal comprises 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 chargers installed evenly along the ASC TPs: the extra lifetime costs compared to a diesel AGV fleet are equal to 1,940,822 euros. Consequently, this configuration has been evaluated further on its sensitivity to changes in diesel, electricity and Lithium-Ion battery prices, cost parameters which are likely to vary in the (near) future.

From this scenario analysis, it was observed that especially future increases in diesel price result in a positive TCO for battery-electric AGVs. This is explained by the fact that, unlike AGV maintenance costs, improvement in operational expenditures is mostly made by the reduction in fueling costs, which cause around 25% of the total costs of ownership of diesel AGVs while only 6% of the battery-electric AGVs' lifetime costs. With this in mind, it can easily be reasoned that especially the diesel price is a decisive factor in determining the financial feasibility of battery-electric AGVs when compared to diesel AGVs rather than the electricity price: slight increases in diesel prices substantially influence the TCO of diesel AGVs and thus the cost difference with electric vehicles. The Li-Ion battery price appears not be a crucial factor for the financial feasibility as even with current Li-Ion price levels battery-electric AGVs prove to be financially feasible and viable over diesel AGVs. Hence, overall it can be concluded that, assuming that the current trend in diesel and electricity prices will continue in the (near) future, battery-electric AGVs prove to be a (far) more cost-effective alternative than their diesel counterpart.

Research conclusions and limitations

Taking the northern side of the ECT Delta Terminal as a case, it was found that opportunity plug-in battery-electric AGVs at the ASC TPs prove to be an operationally and financially feasible alternative to diesel AGVs: operationally under the condition that a sufficient amount of AGVs, charging power and chargers are installed and financially under the condition that the current trend in diesel and electricity prices will continue in the (near) future.

Although this study adds to the understanding of the feasibility of implementing an electric AGV fleet at brownfield container terminals, the performed simulation study and TCO analysis also have limitations. As physical interactions between AGVs have been left out of the simulation model, their operational feasibility may be overestimated since no potential increase in congestion at the ASC TPs has been accounted for. Also, the obtained 'optima' for the studied design variables cannot be considered in isolation from their predefined base case. When also changing the other variables, another optimum may be found: the incorporated designs of freedom made it very complex to find an optimal design configuration which results in the best operational and financial viability. Finally, it is noted that several cost assumptions have been made which not all have been varied by means of a sensitivity analysis. Considering the TCO outcomes as accurate values may hence be misleading; instead, the outcomes presented merely serve as getting an order of magnitude to what extent battery-electric AGVs are a financially feasible alternative to the current diesel fleet.

List of Abbreviations

AGV	Automated Guided Vehicle
ASC	Automated Stacking Crane
DDN	Delta Dedicated North
DDE	Delta Dedicated East
DoD	Depth of Discharge
ECT	Europe Container Terminals
EIA	Energie-investeringsaftrek
FD	Financial Department
I&E	Infrastructure & Equipment
ICE	Internal Combustion Engine
KPI	Key Performance Indicator
LD	Logistical Department
PDL	Process Description Language
QC	Quay Crane
TAT	Turnaround time
TCO	Total Costs of Ownership
TEU	Twenty foot Equivalent Unit
TOD	Technical and Operational Department
TOS	Terminal Operation System
TP	Transfer Point

Contents

List of Figures

List of Tables

1

Introduction

This chapter introduces the performed research. Section 1.1 gives a brief description of this study's context, after which section 1.2 provides the main problem definition. Section 1.3 offers the reader the state-of-the-art in literature and identifies the knowledge gaps relevant for this study. Section 1.4 provides this study's research aim and scope, whereafter section 1.5 elaborates upon the main research question and subquestions to be answered. Finally, this chapter ends with an overview of the chosen research approach in section 1.6, the practical relevance of this study in section 1.7 and this Thesis report's structure in section 1.8.

1.1. Research background

1.1.1. Automated Guided Vehicles

As main ports are becoming more automated due to growing international container trade, transport of containers between sea-side quay cranes and land-side stacking cranes is not being done anymore by human driven trucks. Instead, Automated Guided Vehicles (AGVs), self-driving vehicles that are capable of transporting 20 feet and 40 feet containers between terminals, are used for transport (Kim and Günther, 2006). While automation was initially driven by reductions in labor costs and strikes, additional advantages are predictable operations, increased safety of employees and reduction of errors in the transport process due to automation (Gelareh et al., 2013; Liu et al., 2004). AGVs, which are currently only being used in closed transport systems, navigate by means of Radar, Laser, GPS or Radio Frequency Identification (RFID) technology (Ioannou et al., 2000). Sensors on board and on the infrastructure provide AGVs to communicate relevant characteristics, e.g. location and speed, with a central control system. An onboard controller is directly responsible for the vehicle's driving functions and communicates detected errors with the control operator, which on its turn coordinates the planning of the paths the AGVs are following. An important distinction in AGV navigation is that between *fixed path* and *free ranging*: while the fixed path approach restricts AGVs to drive along predefined location points in a grid structure, free ranging allows the vehicles to drive freely within the operational area.

AGV application in the Netherlands

Probably the best-known application of AGVs in Europe is the deployment of these vehicles at Rotterdam's Maasvlakte I at the Delta Terminal. Europe Container Terminals (ECT), the largest terminal operator in Europe and owner of the Delta Terminal, uses a total amount of 265 AGVs to transport containers from the quay side to the stacking area, covering an average vertical distance of 100 meters with a speed up to 12 kilometers per hour (ECT, 2017). The annual capacity of the Delta Terminal is approximately 4 million TEU[1]. The vehicle fleet navigates by means of RFID technology, which requires transponders into the pavement and readers on the AGV, after which the vehicle is being guided along predefined paths by a Terminal Operation System (TOS). At the stack side, containers are unloaded from the AGV by Automated Stacking Cranes (ASC), which move with a speed up to 16 kilometers per hour. Figure 1.1 shows an overview of the Delta Terminal.

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[1] Twenty foot Equivalent Unit

Figure 1.1: ECT Delta Terminal with quay cranes (right side), automated stacking cranes (left side) and AGVs (in between)

1.1.2. From diesel powered to battery-electric AGVs

As the Delta Terminal can be considered a brownfield terminal, ECT is currently deploying diesel powered AGVs only with a dedicated diesel supply infrastructure. As studied by Van Duin and Geerlings (2011), diesel AGVs pollute by far the most carbon dioxide when compared to other equipment at container terminals in the Netherlands; Figure 1.2 visualizes this comparison. Looking at the trends in formal legislation and market developments towards more sustainability due to increasing pressure on governments and the industry, these diesel AGVs are most likely to become outdated and taken on first in terminal's environmental policy and its corresponding AGV replacement program. For example, on an international level the recent Paris Climate Agreement to reduce global warming to 2 degrees Celsius maximally by reducing carbon dioxide emissions has urged the transportation sector to become more sustainable as this sector alone contributes to one-fifth of the total carbon dioxide emissions in the world (European Environment Agency, 2012; World Bank Group, 2014). Thereby, port authorities around the world, e.g. Hamburg, Singapore and Genoa, are actively promoting sustainable port equipment (Acciaro et al., 2014; Veidenheimer, 2014). In the Netherlands, port authorities collaborate with governmental and market organizations towards a sustainable port in the Rotterdam Climate Initiative (Lodewijks and Welink, 2010). Concrete legislation regarding carbon dioxide emission of diesel AGVs at the Delta Terminal is not there yet, however, when looking at Maasvlakte 2, ECT's neighbors, the APM and RWG terminal, go a step further: they use battery-electric AGVs, an emerging zero-emission technology, only due to environmental obligations (APM Terminals, 2015). Because the Delta Terminal is located at Maasvlakte 1, ECT does not have to fulfill these stringent emission regulations yet. In order to anticipate on future regulations, though, ECT is conducting research on full electric AGVs (Middelburg and Boer, 2017). Whereas diesel AGVs are driven by diesel engines, the propulsion of full electric vehicles is powered by traction batteries. These batteries are able to store and transfer energy to drive an electric engine. The absence of a diesel engine provides battery-electric AGVs to drive without (local) emission of greenhouse gases and noise pollution. Additional advantage of full electric AGVs lies in the driving behaviour of these vehicles at container terminals: as AGVs drive short distances (300-400 meters) multiple times a day between the quay and stack side, the vehicle's motion profile is characterized by low speeds and frequent acceleration (Lin et al., 2003). Because electric engines loose less energy than diesel engines with such a driving profile, the energy efficiency at terminals can be further improved.

1.2. Problem definition

When batteries are running low, they can be charged via a cord to the electricity grid. However, the capacity of batteries in terms of driving distance is considerably lower when compared to internal combustion engines: whereas diesel powered vehicles can drive for 800 kilometers on average, current full electric vehicles

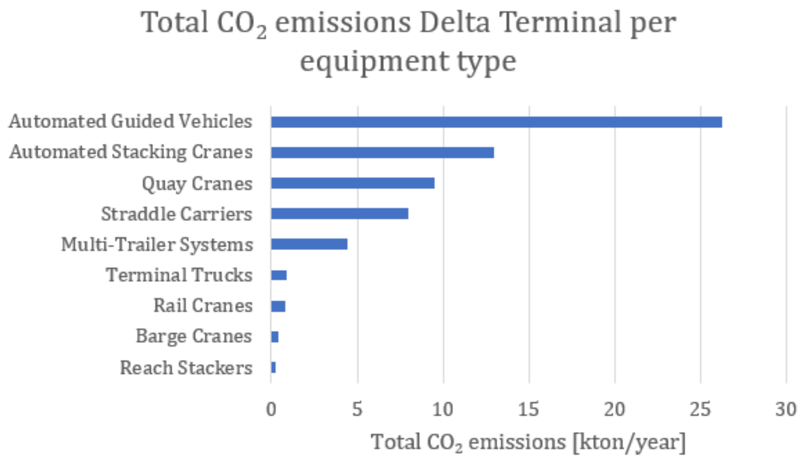

Figure 1.2: Comparison of carbon dioxide pollution AGVs with other terminal equipment at the ECT Delta Terminal (Van Duin and Geerlings, 2011)

on the market reach 250 kilometers at most (INL, 2016; Shen et al., 2016). For full electric AGVs, the driving range is 8-12 hours, compared to a driving time of 1-2 weeks for diesel powered AGVs given an equal transport demand (Campanari et al., 2009; Middelburg and Boer, 2017). Also, the replenishment time of batteries for electric AGVs is substantially longer than the refueling time of the diesel tank for diesel AGVs. While the current diesel AGVs are fully tanked within 5-10 minutes, battery-electric AGV manufacturers Kalmar and Konecranes/Gottwald and charging infrastructure suppliers Heliox and Stäubli promise fully charged batteries within 30-60 minutes[2] (Heliox, 2018; Kalmar, 2018; ZPMC, 2018). This limited driving range and significantly longer replenishment time raises questions about the operational feasibility of deploying electric vehicles, especially in transport systems running 24 hours a day. With the port of Rotterdam, including the Delta terminal, being the main sea entrance to Europe, frequent charging of the port's vehicle fleet may lead to higher downtimes, which is highly undesirable as container transport is crucial for the total terminal productivity.

Operational downtimes of electric vehicles can potentially be overcome by designing and operating its corresponding charging infrastructure in such a way that this does not affect the container transport process. However, brownfield terminals such as the Delta Terminal are limited in both their terminal design and operational flexibility to account for charging battery-electric AGVs. Unlike greenfield terminals which can be designed from scratch, e.g. the APM and RWG terminals, the Delta Terminal faces severe space restrictions as almost all terminal space has been allocated for container operations. Also, adjusting the operational process to charging battery-electric AGVs is highly undesirable as charging is considered a subprocess of the main process, container transport. Consequently, brownfield terminal operators do not know if it is operationally feasible to replace their diesel AGV fleet by battery-electric AGVs, given that the corresponding charging infrastructure must fit in both the existing terminal layout and operational process.

Although battery-electric AGVs are a zero-emission transport alternative and thus sound promising from a societal perspective, terminal operators generally consider two criteria in their selection of port equipment: operations and costs (Steenken et al., 2004). Next to operational concerns, electric AGVs also require higher investment costs in both vehicles and charging infrastructure when compared to diesel AGVs. Although electric propulsion is expected to result in lower operational costs by the reduction in fueling and maintenance costs (Schmidt et al., 2015), brownfield terminal operators do not know if these fuel and maintenance savings over an electric AGV's lifetime outweigh the higher initial investment costs in batteries and infrastructure.

This lack of knowledge on the operational and financial feasibility of battery-electric AGVs compared to the current diesel AGV fleet has created a bottleneck for brownfield terminal operators to make a well funded decision whether or not to purchase battery-electric AGVs for their next AGV replacement program (Middelburg and Boer, 2017).

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[2] Information retrieved during presentations of Kalmar and ZPMC held at ECT Delta Terminal Rotterdam

1.3. Battery-electric AGVs at brownfield ports: lack of scientific research

Although electric vehicles pose serious concerns about the operational viability in 24 hours operations, implementing electric charging in closed transport systems, e.g. seaports, may also be beneficial due to the central control of all vehicles operating in the area (Schmidt et al., 2014). The large scale diffusion of private electric vehicles especially stays out because of a lack of control: car manufacturers, governments and even charging companies lack energy consumption and vehicle operating times data to make well-funded predictions about optimal charging locations. However, for full electric AGVs operating at seaports this data *is* available due to the presence of a TOS, making the vehicle's driving pattern much better predictable.

Despite the great potential electric charging of AGVs at terminals may have, little research has been conducted on this topic (Le Anh and De Koster, 2006). Most studies on AGVs in container terminals use simulation to optimize routing and scheduling algorithms; they ignore the effect of electric charging of the batteries on the operational performance or consider it to be small (Duinkerken et al., 2006; Duinkerken and Ottjes, 2000; Liu et al., 2002; Stahlbock and Voß, 2008; Yang et al., 2004). However, as mentioned before the AGVs have to be charged more frequently due to a lower driving range, which may lead to serious downtimes.

Studies that *have* conducted research on electric charging of AGVs mainly focus on the total costs of ownership. Schmidt et al (2014) investigated the effect of different charging strategies on total AGV costs. By analyzing data gathered from a comprehensive electric AGV project of the largest terminal operator of Germany using battery swapping as charging strategy and Lead-Acid batteries as energy storage unit, they found that shifting battery charging to electricity grid's off-peak hours results in the highest cost savings (terminal operators can even get paid for consuming electricity to stabilize the power grid). On the basis of a simulation study, Schmidt et al (2015) explored the minimum amount of exchange batteries required for a full electric AGV fleet to maintain the required operational performance (the so-called battery-to-vehicle ratio). By analyzing data gathered from another large electric mobility project and by performing a total costs of ownership analysis, they found that using a ratio of 16:10 (16 batteries per 10 AGVs) could lead to 14% cost savings compared to the total expenditures for an AGV fleet; the terminals of APM and RWG at Maasvlakte 2 manage a 15:10 battery ratio (APM Terminals, 2015). Finally, Ebben (2001) shows by means of simulation that the number of batteries to be purchased for automated transportation networks does not heavily depend on the number of battery charging locations but merely on the battery type used. Ebben also proposes a cost trade-off model to help the designer choose the type and optimal number of batteries for the transport fleet.

The current level of battery technology generally provides five types of batteries: Lead-Acid, Nickel-Metal Hydride, Nickel-Zinc, Nickel-Cadmium and Lithium-Ion (Khaligh and Li, 2010). Whereas Lead-Acid batteries yield a low-cost power source and are widely deployed, Lithium-Ion batteries are promised to be the next-generation batteries for electric vehicles due to their high energy density, long battery life (up to 1000 cycles) and recyclability.

Although the studies discussed above seem promising in the field of AGV electrification, they all considered the batteries to be charged by means of a battery swapping station, in which empty batteries are replaced by spare ones. Since brownfield terminals, and specifically the Delta Terminal, often have limited space and flexibility left in their terminal design for these large charging facilities, these options are less viable from a terminal operator perspective. Yet, terminals *do* offer, due to their closed nature, more alternatives for charging batteries, i.e. by means of quick charging at strategical locations (Le Anh and De Koster, 2006; McHaney, 1995). McHaney (1995) somehow included this potential in his research and presented three types of charging schemes to be simulated:

1. Automatic charging, in which AGVs with low batteries (at a certain level) are assigned for charging by a scheduler

2. Opportunity charging, which uses waiting and idle times in an AGV's transport cycle to charge the battery

3. Combination of opportunity and automatic charging

McHaney (1995) concluded that battery constraints cannot be ignored when modeling and simulating an AGV system. Furthermore, he has shown that opportunity charging contributes to a more efficient AGV fleet. However, this research mainly embedded *general* AGV systems in Discrete Event Simulation rather than focusing on embedding automatic/opportunity charging strategies in container terminals. With terminals operating 24 hours a day and handling large ships with an amount up to 7500 TEU, the model of McHaney simply cannot be used. Moreover, in his study McHaney did not include the cost element while costs, next to operations, are the main selection criterion for terminal operators to purchase port equipment (Rijsenbrij and Wieschemann, 2011). Finally, McHaney did not incorporate Lithium-Ion batteries in his research; these batteries, however, provide high energy densities, making battery constraints possibly unnecessary to include in contemporary research on the operational feasibility of battery-electric AGVs at container terminals.

In their conference paper, Fatnassi and Chaouachi (2015) propose a battery charging management strategy for AGVs in warehouses and factories by using linear programming heuristics. However, AGV deployment in factories, as opposed to container terminals, is characterized by long driving distances and short idle times, thereby limiting the potential of opportunity charging in these settings; for container terminals, driving distances are mostly short and waiting and idle times long. Also, Fatnassi & Chaouachi (2015) considered battery charging at the edge of the operational area only. Though, as McHaney (1995) mentioned, incorporating charging infrastructure in the transport cycle may result in higher operational effectiveness. Similar to Fatnassi & Chaouachi's research, several studies have been conducted on the charging state estimation of batteries (Oliveira et al., 2011; Vivaldini et al., 2013): all these studies, though, focus merely on robotic warehouse and manufacturing equipment rather than terminal equipment and characteristics.

Bian et al. (2015) studied the dispatching of electric AGVs in fully Automated Container Terminals (ACT). By developing an event-driven assignment algorithm in which AGVs accomplishing jobs were considered as a linear min-sum assignment model, they concluded, similar to McHaney (1995), that battery capacity constraints cannot be ignored when deploying electric AGVs. Though, Bian et al (2015) go a step further and set up, by means of numerical experiments, an optimal assignment algorithm for dispatching electric AGVs. Yet, Bian et al (2015) focused on ACTs with long AGV traveling distances; most container terminals, however, are characterized by short and frequent trips. They also excluded simulation from the research scope: although optimal assignment algorithms can still be determined with numerical evaluation, stochasticity cannot be captured with this method while container terminals are characterized by stochastic events (in terms of container arrival and handling times). Finally, Bian et al (2015) did not explicitly mention by which means AGVs are charged; they incorporated this event as an interruption in the container pick-up and delivering process.

1.3.1. Knowledge gaps

From this literature review, it can be concluded that there is a clear knowledge gap in literature regarding the **operational** and **financial** feasibility of a battery-electric AGV fleet at **brownfield container terminals**. For greenfield terminals with terminal layout freedom, the study of Schmidt et al. (2015) may suit well: battery-electric AGVs appear to be operationally and financially feasible if large battery swapping stations are used for battery charging. However, for brownfield terminals this study misses the fundamental characteristic that distinguishes brownfield from greenfield terminals: space and operational restrictions.

Regarding the studies of McHaney (1995) and Fatnassi and Chaouachi (2015), the setting in which AGVs are deployed is a factory with short idle times and long driving distances. Container terminals, on the other side, provide short driving times between the quay cranes and the stack and relatively long waiting and idle times (e.g. due to berthing of ships). Outcomes of these studies may thereby not be generalizable to all types of closed transport systems.

Finally, most studies on electric AGV charging consider Lead-Acid battery technology only for deployment at container terminals due to its maturity. Studies that *have* taken into account various battery types for electric AGVs, however, have not yet considered the newest technology with a high energy density: Lithium-Ion batteries. With the rise of Lithium-Ion batteries, battery constraints on AGV's driving range may potentially be ignored and is therefore worth investigating. On the other side, Lithium-Ion batteries are significantly more expensive than conventional batteries and may press on total terminal costs (Schmidt et al., 2014).

1.4. Research aim and scope

The aim of this study is to gain insight into the operational and financial feasibility of replacing diesel AGVs by a battery-electric AGV fleet at brownfield container terminals with space constraints. While brownfield terminal operators face the energy transition towards environmental friendly AGVs, literature does not provide insight into the impact of this transition on their most important criteria: operations and costs. In order to make a well funded decision, though, this study aims at getting this impact more clear by providing a design of the AGV charging process for brownfield terminals and assessing this design on its operational and financial performance. Since a coherent design of battery-electric AGVs's charging process is missing in literature for *brownfield* terminals, chosen is to conduct a design study by incorporating the main functions the charging process has to fulfill.

Considering the scope of this study, two aspects are considered. The physical scope of this research comprises the northern side of the Delta Terminal, i.e. the DDN; the layout of the Delta Terminal is graphically represented in Figure 1.3. As can be seen, the DDN side is the smaller side of the Delta Terminal and the DDE the larger side, both in terms of space and container throughput. Chosen is for the DDN instead of the DDE since battery-electric AGVs are expected to be implemented here first: the shorter quay wall results in shorter AGV driving distances which makes this side a more suitable place for piloting with battery-electric AGVs with limited driving ranges. Regarding the design scope of this study, this research is scoped to a functional design of the AGV charging process only. Although multiple processes can be distinguished with AGV deployment, e.g. container transport and maintenance, this research focuses on designing the charging process without changing the main terminal process, i.e. container transport. Moreover, a functional design is given in which the most important functions the charging process has to fulfill are designed such that this leads to operational and financial feasibility for the terminal operator.

Figure 1.3: Layout of the Delta Terminal with northern side, DDN, and southern side, DDE

1.5. Research questions

From the aim and scope of this study, the following research question is formulated:

Is it operationally and financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?

In order to answer the main research question, several subquestions have been formulated.

1. How are diesel AGVs currently operated during daily transport operations at the Delta Terminal and how is tanking fitted into this process?

This first subquestion aims at gaining a better understanding of the terminal's physical and operational system in order to set boundaries within which AGV charging process designs must fit. More specifically, the current transport process of diesel AGVs will be operationalized such that this can serve as input for the functional design of battery charging.

2. Where in the AGV operational process occur opportunities for battery charging?

Since AGVs are transporting containers 24 hours a day and 7 days a week, this subquestion aims at identifying moments in the operational process which can be used for future battery charging of AGVs. Although container transport is a continuous task which never stops, the actual execution merely has a discrete character, where port equipment is sequentially waiting for other equipment to finish their task. For example, a quay crane waits for a berthing ship to moor before discharging the ship while an AGV is subsequently waiting for a quay crane to load a container on top. These waiting times, and AGV idle times in between two jobs, could more effectively be used by charging the AGV battery.

By analyzing diesel AGV data of the Delta Terminal, an average AGV's cycle time and pattern will be obtained which will be used to get a clear overview of the several steps in the transport process and to find moments and locations of high AGV idling and waiting times.

3. Which design of the charging process can be used for further evaluation based on brownfield terminal operator's requirements and constraints?

Recalling the design scope of this research, the future battery-electric AGV charging process is considered only. In order to evaluate the operational and financial feasibility of battery-electric AGVs, a concrete design that is implementable at brownfield container terminals must be come up with, which also complies with brownfield operator's operational and physical requirements and constraints. By functionally decomposing the charging process into its main system functions, alternative designs are generated from which a complete functional design is selected for further evaluation.

4. How does the selected design influence the operational performance when compared to diesel AGVs?

An important conclusion of the literature review in section 1.3 is the lack of scientific research on the operational and financial feasibility of battery-electric AGVs at brownfield terminals. This subquestion aims at tackling this research gap by incorporating the functional design of the previous subquestion into a simulation model, which will be developed for this purpose. The operations of AGV transport systems at container terminals have been simulated by a lot of researchers (Grunow et al., 2006; Kim and Bae, 2004; Liu et al., 2002; Yang et al., 2004). Yet, a few of these studies have been specifically applied to the Delta Terminal in Rotterdam. Duinkerken & Ottjes (2000), Duinkerken et al (2006), Ottjes et al (2002) and Ottjes et al (2006) developed simulation models in TRACES and TOMAS in Delphi software, specifically for the Delta Terminal at Rotterdam. However, none of the above studies incorporated refueling, let alone electric charging of AGVs into the transport cycle. Since battery constraints cannot be ignored (McHaney, 1995), this will be included in this study.

For this study, discrete event simulation software will be used to develop a simulation model of the Delta Terminal. Chosen is for discrete event rather than continuous simulation since AGV processes also have a very discrete character: various actions can be distinguished at distinct moments in time (container loading, unloading and movement between the quay wall and stack). More specifically, discrete event simulation according to the *process interaction* worldview, which considers systems to be sets of concurrent, interacting processes (Banks and Carson, 1985), will be applied as deep sea container terminals are characterized by concurrent elements, e.g. quay cranes (QC) which request AGVs to transport their containers by interacting with them. State changes occur due to interaction between object processes over time, while time consuming and synchronizing statements can hold the model state for a particular moment of simulation time. In contrast, *event scheduling* describes state changes as a result of advancement of simulation clock time and *activity scanning* comprises the description of actions of objects and the conditions for these actions to take place (Nance, 1981). Consequently, process interaction simulation combines the run-time efficiency of event scheduling with the modeling efficiency of activity scanning.

5. To what extent is the design financially feasible when compared to diesel AGVs?

The aim of this subquestion is to assess the economic feasibility of the design of the third subquestion. By means of a Total Costs of Ownership (TCO) analysis, which Ellram (1993) defined as "all costs associated with the acquisition, use, and maintenance of an item instead of just the purchase price", the functional design will be financially evaluated. Schmidt et al (2014) and Schmidt et al (2015) applied TCO analyses to compare battery-electric AGVs, charged by battery swap and using Lead-Acid batteries only, to diesel powered AGVs. Their framework of cost elements that are included when deploying diesel powered or battery-electric AGVs is shown in Figure 1.4. This framework will also be used in this study since it covers the most relevant cost aspects. However, whereas Schmidt et al (2015) limited their research to battery swapping stations only as charging alternative, this study will also cover other charging techniques. Furthermore, whereas Figure 1.4 leaves out the economic damaging effect battery-electric AGVs may have on the terminal performance (extra costs due to delays in turnaround times of vessels), this study aims at taking these downtime costs into account.

By means of a literature research and interviews with ECT, insight is given into the costs depicted in Figure 1.4.

1.6. Research approach

To answer the main research question and subquestions effectively, a systems engineering approach is highly recommended to use since the design of the AGV charging process cannot be seen in isolation from the core

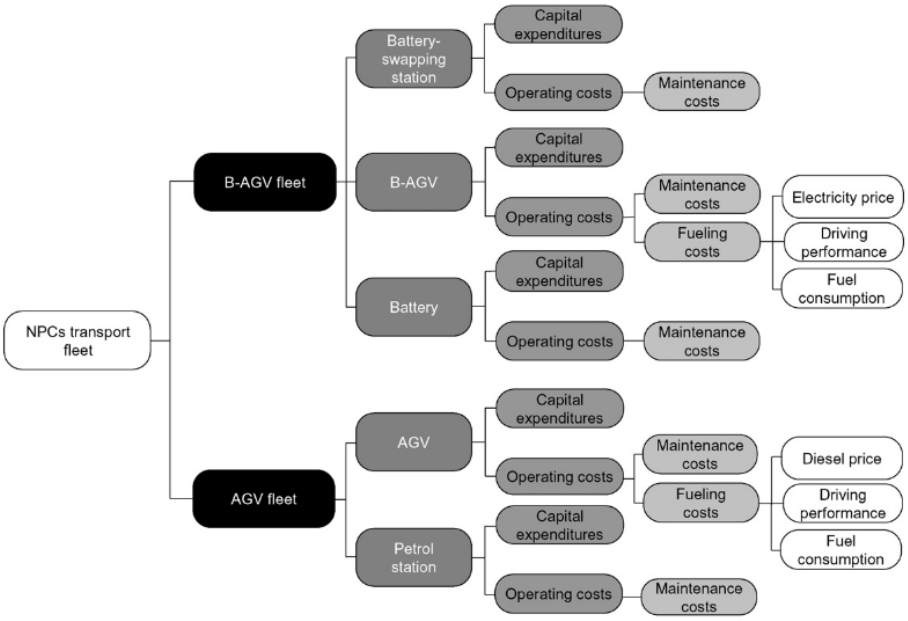


Figure 1.4: Cost elements of diesel powered and battery-electric AGVs (Schmidt et al., 2015)

port process: container transport. Therefore, AGV electrification must be designed *with regard to the context in which it is operating* for which systems engineering is well suited. Sage and Rouse (2009) propose in their *Handbook of Systems Engineering and Management* a widely used systems model that covers the complete design process from identification of objectives to the selection of alternatives to be implemented. This model is shown in Figure 1.5; a division can be made in four distinct phases:

1. Formulation of objectives and constraints
2. Development of alternative designs
3. Development of tests and testing alternatives
4. Selection of alternative design to be implemented on the basis of test outcomes

For this research, an adapted version of the design approach of Sage and Rouse (2009) has been developed for use as main research approach. As a current state or research object analysis is missing in the approach of Sage and Rouse (2009), this will be added in this study to gain a proper understanding of the current AGV operational process. More specifically, to answer the research questions, three phases must be sequentially traversed:

1. **Research object analysis**, in which the current state in container transport operations will be analyzed. By operationalizing the AGV operational process, the most promising moments and locations for battery charging are obtained and subsequently used as input into the design phase. The most important tool be used for this phase is statistical data analysis.
2. **Development of alternative designs and selection**, in which functional designs of the AGV charging process are generated by means of a morphological chart. Morphological charts make use of independent design functions or characteristics which are listed in a chart, after which innovative solutions are proposed for each of these functions (Tayal, 2013). Based on predefined design requirements and constraints from the perspective of the terminal operator, which are obtained by interviewing this study's problem owner, a selection is made from the list of developed alternatives.
3. **Development of tests and evaluating the selected alternatives**, in which the selected design is evaluated on its operational and financial feasibility by means of simulation and a TCO analysis.

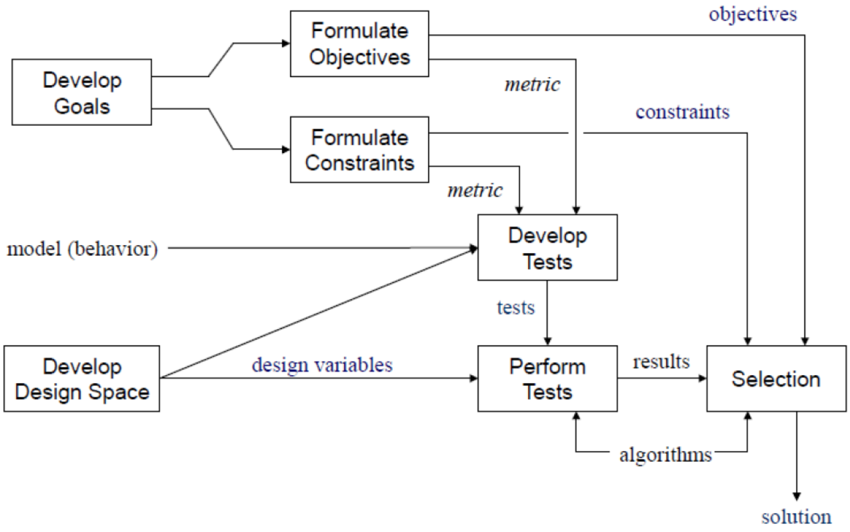


Figure 1.5: Systems model of the design process (Sage and Rouse, 2009)

1.7. Practical relevance of the study

Since ECT has planned its next AGV replacement program within 5 years, this study will support the problem owner in gaining insight into the operational and financial feasibility of battery-electric AGVs by providing a functional design of the AGV charging process and assessing this design on its operational and economical performance compared to the current diesel AGV fleet. More specifically, this research will not only inform the problem owner *if* battery-electric AGVs are a feasible alternative but also *how* this type of AGVs can become feasible (i.e. under which conditions).

1.8. Structure of the study

Based on the chosen research approach, this thesis study is conducted and reported according to the research flow diagram presented in Figure 1.6.

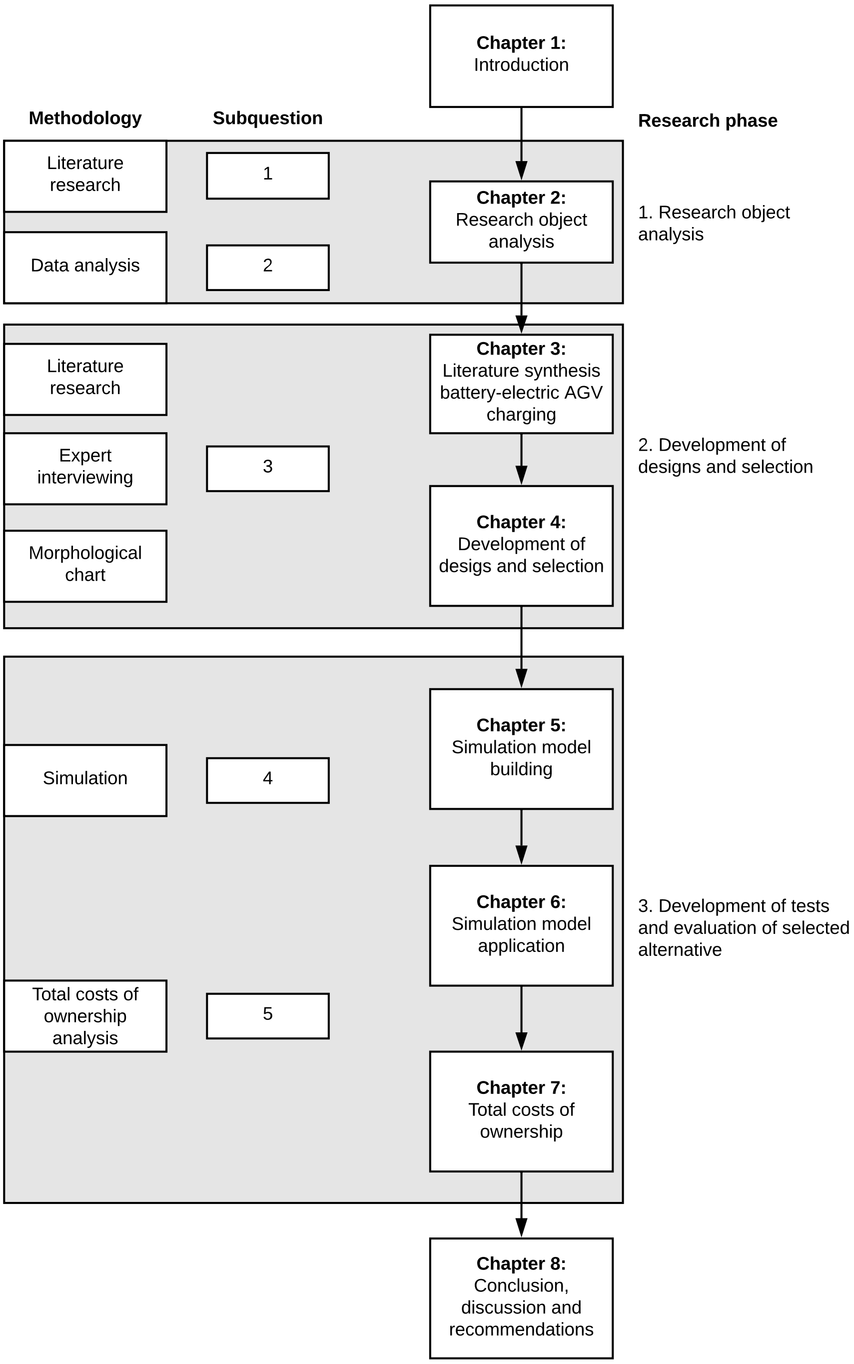


Figure 1.6: Research flow diagram of this study

2

Research object analysis

This chapter aims to answer the first two subquestions,

1. How are AGVs currently operated during daily transport operations at the Delta Terminal and how is tanking fitted into this process?
2. Where in the AGV operational process occur opportunities for battery charging?

by analyzing both the physical layout in section 2.1 and operational processes of container terminals in which AGVs are involved in section 2.2. Thereby, this chapter is setting the physical and operational scope which will be used as input into the design phase and the simulation model. Also, the current state analysis of the system considered and identification of operational performance indicators will be useful for the building and validation of the simulation model in Chapter 5. By zooming in on AGV operations and tanking in section 2.3, all activities in an AGV's operational cycle are listed and analyzed to look for opportunities for battery charging in section 2.4. The main methodologies used in this chapter are literature research and statistical analysis of AGV data obtained from ECT's operational database. Figure 2.1 graphically shows the structure of this chapter with the main output and relations between the sections.

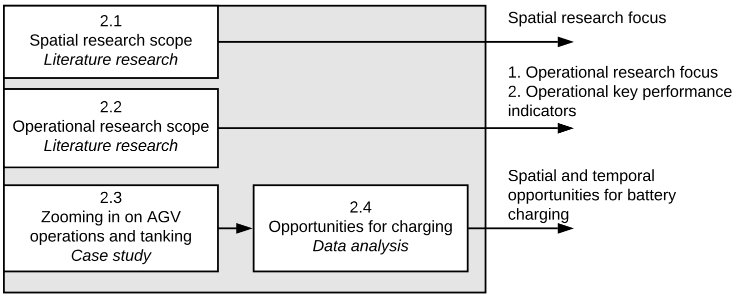


Figure 2.1: Structure, methods and output of Chapter 2

2.1. Spatial research scope

Previous to the design phase, the current physical layout of container terminals in general and the Delta Terminal in particular is analyzed. A general layout of the Delta Terminal is already provided in Chapter 1; a distinction can be made between the DDN, where 65 AGVs are operating, and the DDE, having a substantial larger amount of 200 AGVs. As already mentioned in section 1.4, this research is scoped towards the DDN which follows the usual layout of a container terminal shown in Figure 2.2. Generally, five physical areas can be distinguished for both loading and unloading operations (Van Ham and Rijsenbrij, 2012):

- *Quay area*, where ships berth, varying from deep sea vessels with a capacity up to 21.000 TEU (CMA-CGM, 2017) to small barge ships, and containers are being loaded/discharged

- *Water side transshipment area*, where transshipment of containers from stack to ship and vice versa takes place.

- *Stack area*, where containers, destined for either land or water transport, are temporarily being stored for further transport. This storage time creates a buffer for the corresponding transport modality to arrive and/or get ready

- *Land side transshipment area*, where containers are being transported from stack to land transport modalities and vice versa

- *Land side area*, where land transport modes arrive/depart to (un)load containers destined for oversea/hinterland locations

Various equipment is responsible for container transport in the areas distinguished above. While large quay cranes (QC), stationed at the quay with a reach up to 25 rows (Stahlbock and Voß, 2008), are responsible for vessel loading and unloading, AGVs are often deployed in the water side transshipment area for continuous stack-ship transport of containers; though, other types of horizontal transport modes may also act as main mode. Stahlbock and Voβ (2008) classify ship-to-yard mode into *active* and *passive* vehicles: while active vehicles are able to lift containers by themselves (e.g. Automated Lifting Vehicles, straddle carriers), cranes and other equipment assist passive vehicles in (un)loading containers (e.g. AGVs, multi-trailer trucks). The stack area, also called container yard, is generally equipped by Rail Mounted Gantry (RMG) cranes, also referred to as ASCs, which are responsible for (un)loading of containers from/onto transshipment modes and for organizing the stack block by repositioning containers (Van Ham and Rijsenbrij, 2012). The land side transshipment area usually deploys straddle carriers (SC) or reach stackers (RS) for land transport (un)loading. Finally, trucks and trains are mostly present in the land side/hinterland area.

2.1.1. Research focus

Due to the deployment of AGVs in the water side transshipment area, this research mainly comprises this area, which is marked yellow in Figure 2.2, and to a lesser extent the quay and stack areas. The setting of this scope is mostly important for both the designs and simulation model to be developed for electric AGV charging, for which it is preferable to study a *closed* system. As the AGV area is mostly closed, with open interfaces to QCs and ASCs, this implies full controllability of the research object, since QCs and ASCs are also controlled by the terminal operator (Kim and Günther, 2006). Important implication is also the extent to which the involved areas must be modeled: the water side transshipment operations in more detail than QC and ASC operations. Finally, although vessel operations, i.e. the quay area, are not the focus of this research, these operations are included as representation of the 'environment', resembling arrival patterns of containers to be transported, and are thus less detailed investigated.

2.2. Operational research scope

The logistic operations at container terminals can be systematically described in several ways, of which a frequent used one is the *PROPER* model which incorporates inflow and outflow of *products*, which are being handled by the process, *orders*, which demand products to be handled, and *resources*, which are being exploited for the handling of inflowing products (Veeke et al., 2008). By means of a PROPER model it can immediately be seen on a high level what system is considered and what its main inputs, outputs, resources and performance indicators are. This is especially suited for the building of the simulation model in Chapter 5. A graphical representation of the PROPER model structure is depicted in Figure 2.3.

2.2.1. Order, product and resource flow

For container terminals, the order, product and resource flow are respectively *mooring ships* which demand (un)loading of containers, *containers* which' status changes from unhandled to handled at the moment the container is either being loaded onto a ship or unloaded onto an AGV (and subsequently being stored in the stack area), and *equipment* responsible for transport/transshipment in the water side transshipment area, i.e. QCs, AGVs and ASCs/RMGs. In order to maintain the main process flow (Operate), which reflects the transshipment of containers, both demand from ships to be (un)loaded (Perform) and availability of resources to be exploited (Use) are necessary.

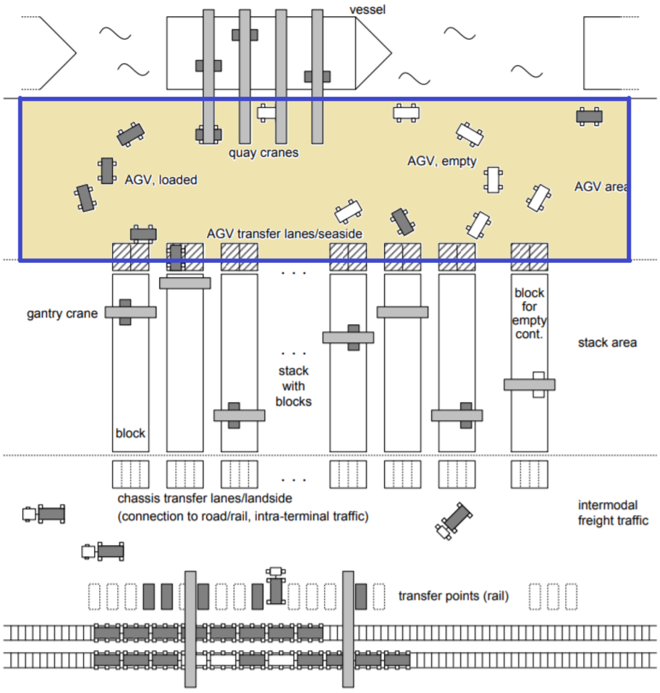


Figure 2.2: General terminal layout (Stahlbock and Voβ, 2008)

2.2.2. Performance and requirements

For the performance and requirements, further insight is needed into water side terminal KPIs from a logistical perspective. Esmer (2008) provides a comprehensive categorization of container terminal performance measurements into *production*, *productivity*, *utilization* and *service* measures; this classification is also used in this section.

Main production measures, which consider throughput of containers, i.e. quantities passed per time unit, are mainly ship and quay transfer throughput. Ship throughput resembles individual ship's container loading and unloading rate; quay transfer throughput spans the entire container flow over the quay wall.

Productivity of the QCs, AGVs and ASCs can be operationalized into number of moves made per hour, where a move represents the combination of hoisting a container from either an AGV or ship and dropping the container onto either an AGV or ship (Vis and De Koster, 2003). Mentioned by many researchers, QC productivity seems to be one of the most important KPIs as a higher productivity leads to lower mooring times, or turnaround times, of arrived vessels (Kim and Günther, 2006). Main reason is the delay in mooring, or turnaround time, that occurs if QCs achieve low productivities: this delay will eventually affect the arrival and departure time of consecutive ships, leading to *cumulative drift* of delays. Moreover, AGV and ASC productivity, measured in number of containers moved per hour, are also important in determining the water side terminal performance.

QC, AGV and ASC utilization, which reflects the ratio of active working time over the total service time, thus including waiting and idle time, must be as high as possible to ensure idle time is being minimized. However, while there is no limit on QC and ASC utilization - the purchase costs are simply too high and in the AGV system, they resemble the 'customers' waiting in line for a pay desk - an AGV utilization rate near 100% is undesirable due to the transport system becoming unstable non-linearly after the 80% threshold (Henesey et al., 2008). As a result, waiting times of QCs and ASCs on AGVs will also increase non-linearly. Redundancy of spare AGVs is therefore to a certain extent required. The stress on QC utilization in literature is being confirmed by ECT experts from the Logistical Department, who state that crane performance is leading in assessing the overall water side terminal performance; moreover, the number of times and the average time QCs have to wait for AGVs also determine the water side performance.

Service measures mostly comprise the turnaround time of ships in hours; in consultation with ECT experts from the logistical department (see Appendix J), an increase of one hour in vessel mooring time could count up to 5,000-10,000 euros penalty per ship.

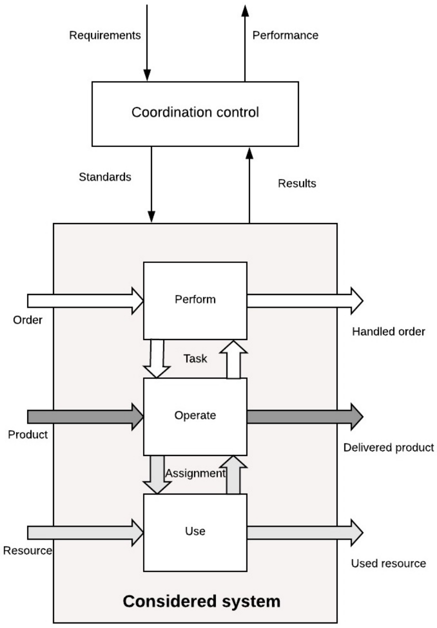


Figure 2.3: General PROPER model structure (Veeke et al., 2008)

As a final remark, Esmer (2008) does not mention the (energy) efficiency of AGV trips; yet, AGVs may either drive with or without a container. Empty drives are considered worthless as no containers are being handled; these rides comprise either driving to a new container or, as is current practice at the Delta Terminal, driving to an ASC that is closer by ships that will arrive shortly afterwards. From an efficiency perspective, the fraction of empty rides must be minimized, e.g. by choosing the nearest AGV to drive to the QC or ASC (Vis and De Koster, 2003).

2.2.3. Final PROPER model

The developed PROPER model for container terminals is depicted in Figure 2.4. The KPIs described above have all been applied, in consultation with ECT experts from the logistical department (see Appendix J), to the Delta Terminal in order to be able to validate the simulation model in Chapter 5. First, the current QC utilization, including waiting for AGVs, labor shift changes and failures, fluctuates around 70%; AGV utilization's value lies somewhere between 70 and 80%. For a more extensive calculation of the remaining KPIs, the reader is referred to Appendix A. For this chapter, it is sufficient to mention that a distinction in mooring times of deep sea vessels (MAINS) and barge vessels (BARGES) has been made in order to allow for structural differences in container discharge and load sizes in the simulation model. As a consequence, mooring times of both types turn out to be 17.6 hours and 3.3 hours respectively.
Three values have been added to the *Standards* which are obtained by analyzing a large data set provided by ECT logistical experts, containing AGV, Crane and load/discharge data of the Delta Terminal. First, the average fraction of time QCs are delayed by AGVs arriving too late has been calculated. Repeated for three random weeks in 2018, this ratio turned out to be 16.8%; as a standard for battery-electric AGVs this value will also be used. Second, the average time QCs have to wait for AGVs in case of no available AGVs has been determined by distinguishing *on time* and *too late* carries of the QC: for on time containers, the average waiting time between two sequential AGV arrivals at the QC is equal to, excluding extreme values, 34 seconds, while for containers being handled too late the AGV inter arrival time is equal to 179 seconds, a surplus of 145 seconds. Finally, the current empty AGV ride fraction is equal to 44.2%: this fraction has been determined by dividing the distance covered by AGVs while not carrying a container on top by the total distance covered in a month (repeated for the months November, December and January).

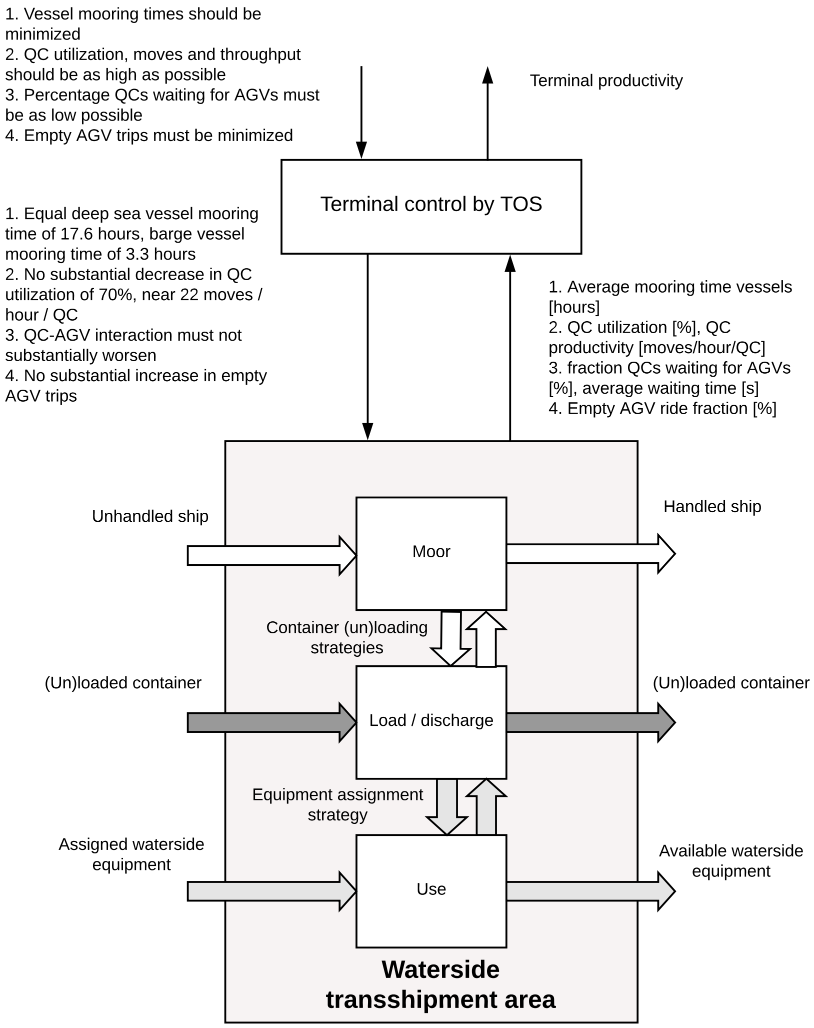


Figure 2.4: Developed PROPER model for Delta Terminal

2.3. Zooming in on AGV operations and tanking

While the PROPER model gives a general overview of inflow, outflow and requirements and performances of the water side transshipment area as a whole, this section aims at zooming in on the AGV operations. Underlying the transshipment of containers at water side from vessel to stack and vice versa is the interaction between ASCs at stack side, QCs at quay side and AGVs driving in between. Figure 2.5 shows the actions and interactions that occur during handling of a container in both directions, i.e. from stack to quay or vice versa. Dotted arrows indicate interaction points between terminal equipment. During the discharge of containers from mooring vessels, QCs hoist containers one after another from the ship and load these containers on AGVs that have arrived at the QC Transfer Point (TP). In case of a late AGV arrival, QCs postpone the hoisting of the container until the AGV has arrived. After loading on the AGV, the AGV drives with the container on top to the TP of the destination ASC. Once arrived, it waits until the ASC unloads the container from the AGV and puts it away in the stack. During the loading of containers onto mooring vessels, exactly the opposite takes place (i.e. from ASC to QC). What can be noticed from Figure 2.5 is that AGVs have two moments in a transport cycle in which they are waiting for either the ASC or QC to perform the next action, i.e. (un)load containers. For the remainder of this study, these moments are referred to as *waiting times*. AGVs also become idle after the transport of a container; for the remainder this is referred to as *idle time*.

When further zooming in on the actual movements AGVs make during either a discharge or loading trip at the Delta Terminal, Figure 2.6 is useful to look at. When discharging a mooring vessel, an AGV starts transporting a container by leaving its idling place, i.e. the ASC TPs (located at the top of Figure 2.6. In a rectangular

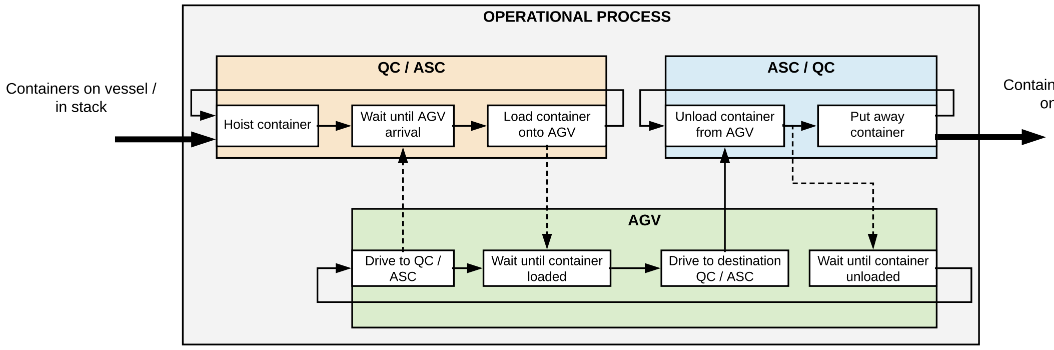


Figure 2.5: Operational process model of container transshipment at water side; dotted arrows indicate interaction between equipment

structure, AGVs drive empty to a QC TP by entering the QC lane via a limited amount of entrance points, which is caused by the movement of QCs as well. Once arrived at the QC lane, the AGV joins the queue of other AGVs waiting for the same QC to load its container on top. All movements until now are marked black in Figure 2.6. When the AGV has arrived at the QC TP, it waits for the QC to load its container after which the AGV leaves the QC lane via another entrance point and drives loaded to the destination ASC. These movements are marked green in the figure. When arrived at the destination ASC, the AGV waits on a TP until the ASC has unloaded the its container. Then, the AGV is either scheduled for a next transport job or becomes idle and starts driving to its assigned idling place on an ASC's TP. One additional move is missing in Figure 2.6 which occurs frequently at the Delta Terminal: AGV prepositioning to an ASC TP closer by a mooring vessel in order to reduce the final driving time to the vessel's QCs. When assigned for a discharge trip, i.e. unloading vessels, AGVs may be assigned to another ASC TP closer by the destination QC before actually driving to this QC in order to improve the terminal's operational efficiency.

Figure 2.6: AGV movements during a discharge trip in black and green and during tanking in red

2.3.1. Current AGV tanking process

Next to the operational process, important is to gain insight into the tanking process of the current diesel AGVs at brownfield container terminals as this is to be replaced by charging with the implementation of battery-electric AGVs. Tanking is considered a subprocess of the main process, container transport. Therefore, the AGV tanking process is fit such that it does not affect the operational process. As a complex decision making process is at the core of AGV tanking, a flowchart is used to visualize this process. A flowchart is "a graphic means of documenting a sequence of operations" and is especially suited for condition based algorithms (Chapin, 2003). Since the AGV tanking process is also condition based, the flowchart as depicted in Figure 2.7 has been constructed for this purpose. A rectangular box reflects an action to take, a diamond shape a condition. The reader is attended on the fact that this system is centrally controlled by the TOS and thus all actions regarding AGV assignment are executed by this control system. Generally, four actions can be distinguished in the tanking of AGVs:

1. notifying the AGV that the diesel tank quantity has dropped or will drop below a threshold level. Considering ECT's AGVs, the first threshold level is 200 liters and the second notification is sent at 100 liters

2. letting the AGV drive to the tanking station. Currently, there is one tanking station with two AGV spots at the DDN located at the edge of the terminal area. In Figure 2.6, this tanking move is resembled by the red dotted line which is pointed towards the edge of the AGV area.
3. tanking the AGV. ECT's AGVs take on average 5-10 minutes for a full tank
4. letting the AGV drive back to the operational area and assign transport job if necessary

As tanking only takes 5-10 minutes, AGV queuing at the tanking station rarely takes place. It is expected that for charging AGV batteries this will occur more frequently, which may lead to higher AGV downtimes. However, it is also observed that within an AGV transport cycle and in between two cycles there exist opportunities for battery charging by using the waiting times for container (un)loading and idle times after finishing a transport job for charging, which are currently not being used by the diesel AGVs.

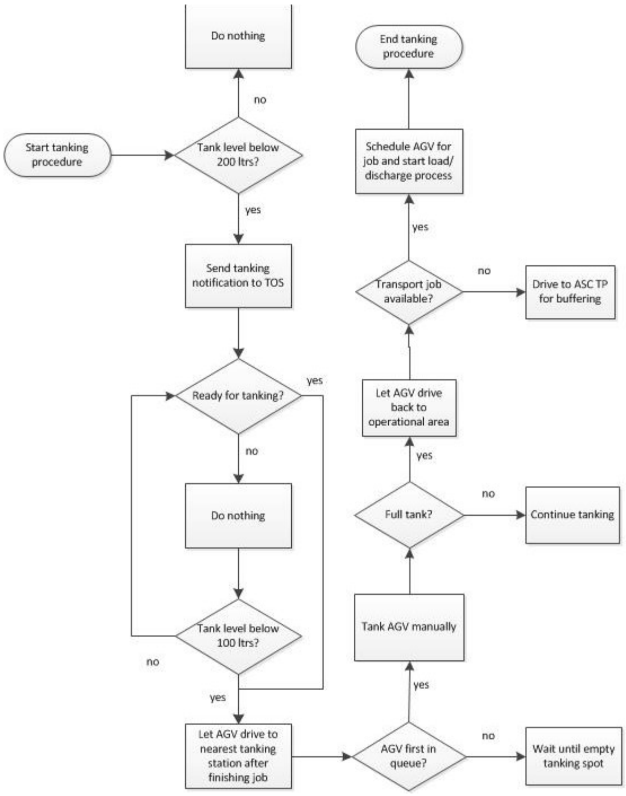


Figure 2.7: Flowchart of AGV tanking procedure

2.4. Opportunities for charging AGV batteries

A detailed overview of all AGV activities during either a discharge or loading trip is given in Appendix B in which the *Timeline AGV Load Delta* and *Timeline AGV Discharge Delta* is presented, provided by the ECT logistical department (see Appendix J), which explicitly visualize all activities each AGV could take within a transport cycle. In this section, the activities with high AGV waiting and idle times are highlighted in order to guide the reader to the determination of locations and moments which are most promising for future charging of AGV batteries.

- Waiting at an ASC TP during (un)loading of a container; the norm states that this activity takes on average 180 seconds. When reading through Chapter 5, it becomes clear that this norm is currently being achieved as the average (un)loading time of AGVs by ASCs equals 151 seconds; however, buffering after (un)loading takes considerably longer, as will be shown in section 2.4.
- Waiting at a second ASC after prepositioning; according to ECT norms, this activity, which is the predecessor of *driving to QC*, takes 120 seconds at minimum. Most of the times this norm is being achieved,

however, irregularities in the AGV-TOS communication system incidentally causes this waiting time to become (very) high.

- Waiting in QC lane; this comprises the moment from entering the QC lane until passing the waitpoint being the next AGV to be handled by a QC. According to the norms, waiting for the QC should not take longer than 240 seconds, however, as will also be shown in section 2.4, this is currently hardly the case due to the cumulative effect of AGVs arriving too late at the QC, which delay the arrival times of other AGVs. Late AGV arrivals are mostly caused by a temporary lack of available AGVs for QCs, though, other causes included are congestion on the way, interruptions in the communication system, bad TOS planning and sensor flaws.

- Not included in the timeline of ECT, while of importance for this study, is the waiting time at an ASC before driving to a QC. That is, the moment in between *waiting at an ASC TP during (un)loading* and *driving to QC*. This waiting time is currently very high as is shown in the next section

- Idle time in between two transport jobs. As the previous activities are all incorporated *in* the transport cycle, idling at an ASC TP takes place in between two transport jobs. For AGVs, especially during non-busy periods, this idle time can count up to 1-2 days.

2.4.1. AGV idle and waiting time analysis

Analyzing an AGV data set with more than 10,000 data points provided interesting results, especially regarding the identification of high idle and waiting times. All actions an AGV takes during a *loading* trip have been statistically investigated; for discharge trips, appropriate data was more difficult to obtain, however, it is expected that possible variations from loading trips are minimal. Figure 2.8 shows the outcome of this analysis in terms of *median* time intervals; as average values were heavily biased by outliers, shown in Table 2.1 and in the figures afterwards (right-skewed distribution), the middle value in the data set is used for representation (i.e. the median). The cause of these extreme values is not fully known, yet, cancellation of scheduled AGVs by ECT's scheduling system DynaCore may be at the core of these outliers. The left side of Figure 2.8 shows median durations in which an AGV is physically active and driving, while waiting times cover the right side of this figure. It can immediately be noticed that waiting times at the ASC, before leaving to the QC, and in the QC lane take up the largest share in the total AGV cycle time (423 and 454 seconds respectively), that is from driving to the first ASC until driving away from the QC after being unloaded; this cycle takes on average 30 minutes, excluding outliers. Idle times in between two transport jobs are on average, taking into account both busy and non-busy periods, 13 minutes. Consequently, the total time in between two subsequent AGV jobs is on average 30+13 = 43 minutes.

Table 2.1: Statistical analysis of AGV drive, waiting and idle time durations

	N	**Mean [s]**	**Median [s]**	**Standard deviation [s]**	**Maximum value [s]**
Drive time from QC to ASC	10006	60.53	67.00	52.71	427
Waiting time at ASC during container unloading	10007	419.97	319.00	450.25	5491
Waiting time at ASC before driving to QC	10005	673.67	423.00	895.15	18543
Prepositioning drive time	1018	110.73	109.00	66.21	409
Waiting time at prepos ASC before driving to QC	1017	761.10	386.00	1323.06	16837
Drive time from ASC to QC lane	10006	92.44	87.00	38.26	444
Waiting time in QC lane before unloading	10006	625.45	454.00	730.80	12989
Drive time from QC waitpoint to QC TP	10002	45.20	15.00	133.25	4596
Idle time between two transport jobs	3891	760.01	745.55	102.37	150031

Although battery charging specifications will be discussed in the next chapter, a rough comparison can already be made with AGV battery charger suppliers, e.g. Kalmar, Heliox, Stäubli and Konecranes/Gottwald, promising fully charged AGVs within half an hour to a full hour (Heliox, 2018; Kalmar, 2018; ZPMC, 2018). Given the separate idle/waiting times at either the stack or in the QC lane, current chargers on the market thus do not provide battery-electric AGVs to be fully charged within one cycle. Yet, it may be unnecessary to fully charge AGVs when implementing the concept of *smart charging*: charging AGVs in harmony with the terminal activity.

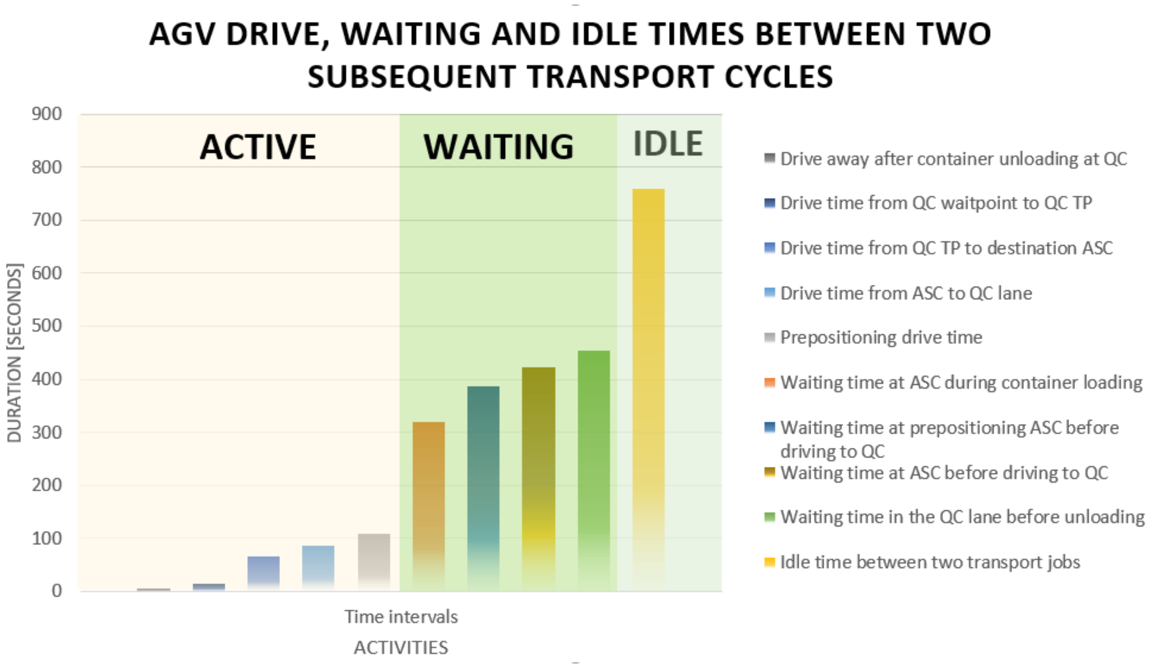


Figure 2.8: Histogram of AGV drive, waiting and idle times between two subsequent transport jobs

2.5. Conclusion

This chapter aimed at describing the physical and logistical operations at container terminals, demarcated to the water side transshipment area of the Delta Terminal, in order to answer the first two subquestions of this study:
1. How are AGVs currently operated during daily transport operations at the Delta Terminal and how is tanking fitted into this process?
2. Where in the AGV operational process occur opportunities for battery charging?
Given the study object as highlighted in Figure 2.2, AGVs drive in a grid structure, i.e. rectangularly, from the QCs to the ASCs with either a container on top or empty. Whereas the AGV elements can be modeled as closed systems, QCs and ASCs require to be modeled with interactions to the quay and stack area respectively; suitable in this case would be to define stochastic distributions for both QC and ASC handling processes into the simulation model. AGVs can either perform a discharge or loading trip: when discharging, an AGV first drives to a QC, where it loads a container on top, after which the AGV drives to the corresponding ASC to unload its container. When performing a loading trip, the AGV drives empty to an ASC, gets a container on top and then drives loaded to the destination QC, where its container is being loaded onto the ship. Tanking of the AGVs only takes place after a threshold value, i.e. 200 liters, has been reached. The AGV then drives to a tanking spot at the edge of the operational area.
Regarding AGV control, central control is currently being applied at the Delta Terminal and at most other deep sea container terminals by means of a Terminal Operation System (TOS), which assigns AGVs to discharge/loading containers, sets routes to be followed by the AGVs and provides interaction with other terminal equipment, i.e. QCs and ASCs. Main advantages of central control over decentral control (e.g. by the AGVs themselves) are the possibility to reach a system optimum and to fully control the system (Ramadge and Wonham, 1989). However, disadvantages lie in the computational complexity for the TOS of dispatching all AGVs and in the risk of total terminal shutdown in case the central controller fails its task (Sycara, 1998).
From literature and interviews with ECT's logistical department, three types of Key Performance Indicators (KPIs) have been defined in order to be used for comparison with a future battery-electric AGV fleet: *productivity, utilization* and *service* measures. Whereas productivity comprises QC productivity in container moves/hour/QC, utilization measures are QC utilization rates operationalized in percentage working time over the total service time. Service measures are operationalized in turnaround times of both large deep sea vessels and smaller barges in hours/berth. Not mentioned in literature but of importance for this study is *ef-*

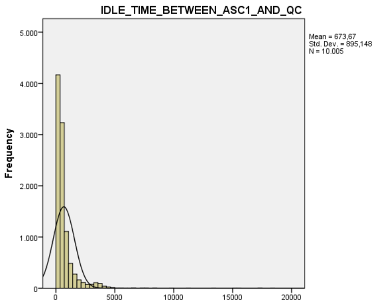


Figure 2.9: Waiting time at ASC before driving to QC

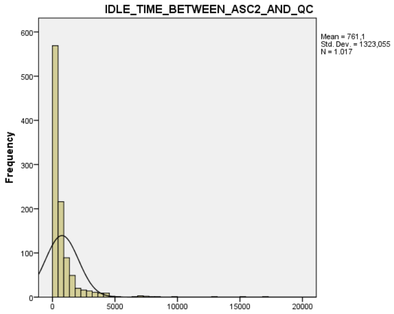


Figure 2.10: Waiting time at prepositioning ASC before driving to QC

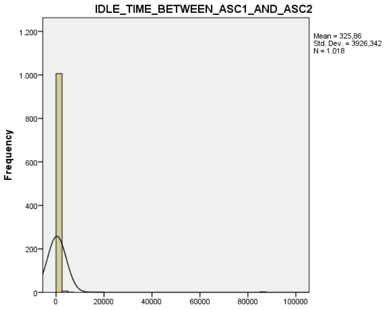


Figure 2.11: Waiting time at ASC before driving to prepositioning ASC

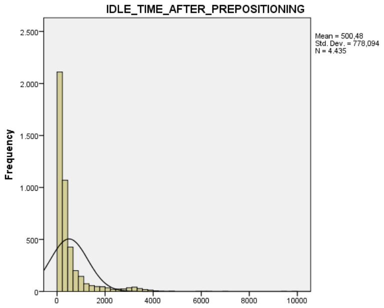


Figure 2.12: Waiting time after prepositioning at ASC

ficiency, operationalized in the fraction of empty AGV trips over the total number of trips made. Main reason for including this KPI is the expected increase in empty trips when battery-electric AGVs have to drive more frequently to a charging spot to charge their batteries.

Regarding subquestion 2, analyzing a large data set of AGV time stamps confirmed that AGVs are either idle or waiting at a QC or ASC Transfer Point for a significant share of the total AGV cycle time (see Figure 2.8). AGV waiting times under the QCs for (un)loading a container and waiting times at an ASC Transfer Point (TP) before driving to a QC (either loaded or unloaded) take up on average 7.5 and 7 minutes respectively on a total AGV cycle time of 30 minutes. When considering other waiting times, e.g. the waiting time at a prepositioning ASC before driving to a QC, this share further increases to two-third of the total AGV cycle time. Moreover, the average idle time in between two transport jobs is 13 minutes, which is about 30% of the total AGV time. This percentage is confirmed by ECT experts which state an AGV utilization rate of 70-80%.

The physical and operational boundaries set in this chapter, together with the given operational key performance indicators, will be used as input for the building and validation of the simulation model in Chapter 5. Furthermore, the fact that AGVs are mostly waiting and idle at the QC and ASC TPs will be used as input into the design of the AGV charging process in Chapter 4, as these idle and waiting times can effectively be used for charging.

3

Literature review on electric AGVs, batteries and charging

This chapter aims at gaining insight into the state-of-the-art in charging battery-electric AGVs which will be used as input into the design of the future AGV charging process and into the simulation model. More specifically, by making a distinction in vehicle, battery and charging infrastructure/deployment this chapter has a merely technical character, whereas the previous chapter was solely logistic/operational. Main reason for incorporating the technical dimension regarding *vehicles* and *batteries* is that relevant vehicle and battery characteristics will be used as input into the simulation model in terms of battery-electric AGV driving performance versus current diesel AGV driving performance. Moreover, by reviewing the current state-of-the-art in charging techniques and strategies and their main advantages and disadvantages, this synthesis will be used as input into the design of the AGV charging process. This chapter starts with a technical comparison of diesel and battery-electric AGVs in section 3.1, in which the focus lies on driving performance, whereafter section 3.2 summarizes the state-of-the art of literature on vehicle batteries. Finally, section 3.3 describes the main charging methods and strategies retrieved from literature which mainly answer the question *how to charge* electric AGVs. This section also synthesizes the found charging methods, battery characteristics and other specifications in order to be used for the evaluation of AGV charging designs in the next chapter. The main methodologies used in this chapter are literature research and expert interviewing. Figure 3.1 graphically shows the structure of this chapter with the main output and relations between the sections.

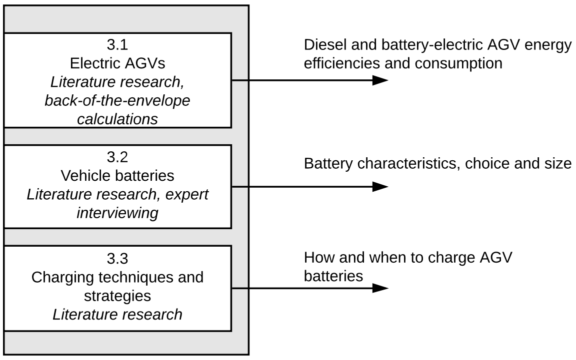


Figure 3.1: Structure, methods and output of Chapter 3

3.1. Electric AGVs

Before elaborating upon battery-electric AGVs, it should be understood why there is, from the perspective of terminal operators worldwide, a preference for electric propulsion over other zero-emission fuel sources. Thomas (2009b), Granovskii et al. (2006) and Campanari et al. (2009) show by means of simulation and a total costs of ownership analysis that, given an equal driving performance, battery-electric vehicles are more cost-efficient than fuel cell vehicles, the only zero-emission alternative next to electric propulsion, when driving ranges do not exceed 210 kilometers, which is indeed the case at container terminals with short AGV driving distances due to their lower purchase and electricity price. A high driving range results in heavier battery packs which deteriorates driving performance; fuel cell vehicles can compensate higher driving ranges with more advanced fuel cells, loosing less on vehicle weight. Specific additional advantages of electric AGVs over fuel cell vehicles are the availability of an electricity grid at container terminals and a higher safety perception: electric batteries are considered safer than hydrogen cells because of the lower impact in case of fire/explosion, which indeed should be minimized taking into account the (hazardous) cargo AGVs need to transport. Finally, as battery-electric AGVs are the only zero-emission alternative currently available, container terminal operators are not left another zero-emission choice.

Having scoped this research towards battery-electric AGVs only, the main technical differences compared to the current diesel AGV fleet are identified in order to be used for the operational evaluation in Chapter 6, where a comparison between battery-electric and diesel AGVs is made. More specifically, by zooming in on the driving performance of both vehicle types it can be roughly estimated to what extent battery-electric AGVs will impact the daily operations at container terminals, as mentioned by McHaney (1995) who stated that AGV energy consumption, battery and charger sizes determine the physical operation of battery-electric AGVs. Whereas batteries and chargers will be discussed in sections 3.2 and 3.3 respectively, started is with a comparison of the energy efficiencies of both diesel and battery-electric AGVs after which the energy consumption for electric AGVs is derived. Driving ranges and replenishment times of both vehicle types have already been discussed in section 1.2; whereas diesel AGVs have a driving range of 1-2 weeks with a full tanking time of 5-10 minutes, batteries of electric AGVs need to be replenished for 30-60 minutes after 8-12 hours of driving. Although this implies a deterioration in transport performance, battery-electric AGVs prove to be more energy efficient as the inefficient diesel engine is replaced by an efficient electrical drivetrain.

3.1.1. Energy efficiency of diesel and battery-electric AGVs

Terex, one of the largest AGV manufacturers for container terminals, provides in its presentation *Battery-Electric AGVs: Clean Air in Ports* a decomposition of both diesel and battery-electric AGVs using Lead-Acid batteries, displayed in Figures 3.2 and 3.3 respectively (Terex, 2013). Considering the diesel AGV, the total well-to-wheel efficiency is approximately equal to 26%. This has been calculated as follows: first, diesel stored in a fuel tank is burned in a diesel engine at a 35% efficiency, after which the resulting heat is converted to electrical energy with a 92% efficiency. The electrical energy is converted from alternating to direct current to provide energy for in-vehicle equipment running on DC with an efficiency rate of 97%, whereafter this DC circuit is transformed in AC again to power the electric motor with an equal efficiency. Finally, the electric motor transforms AC electrical energy into kinetic energy for the wheels with a 93% efficiency. When multiplying all the aforementioned efficiency rates a well-to-wheel efficiency of 26% is obtained.

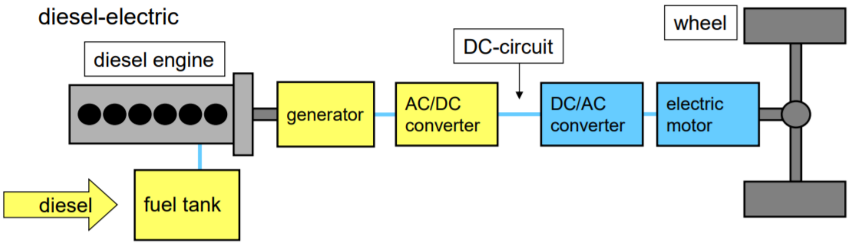


Figure 3.2: Main components of a diesel AGV (Terex, 2013)

For *Lead-Acid* battery-electric AGVs, the well-to-wheel efficiency is more than twice as high: 56%. This is calculated as follows: electrical energy is being charged with an efficiency of 75% into the battery. As the electrical energy is already DC no AC/DC conversion is needed anymore. DC/AC conversion for the electric motors is done with an efficiency rate of 97%; the efficiency of the electric motor is again 93%. Finally, energy loss occurs due to inefficiencies in the vehicle's axles (due to movement, 92%) and because of an increase in vehicle weight (due to heavier battery packs, 90%). Multiplying these efficiency rates results in an overall drive train efficiency of 56%.

Considering this last efficiency, it must be noted that this value is largely the result of the choice for Lead-Acid batteries. When considering the most recently developed battery technology, Lithium-Ion, the charging efficiency lies somewhere between 80 and 90% (Sun, 2010). Also, information retrieved from Kalmar's and VDL's battery-electric AGVs (see Appendix J) shows that there is no increase in dead AGV weight (4 to 5 tons Lithium-Ion battery weight equal to diesel components), which thus potentially implies a higher efficiency for Lithium-Ion batteries when compared to Lead-Acid batteries (Kalmar, n.d.). The well-to-wheel efficiency of Lithium-Ion battery AGVs is thereby, in the most conservative scenario, approximately equal to:

$$0.8 * 0.97 * 0.93 * 0.92 = 0.66 \tag{3.1}$$

As the battery choice for this research will be discussed in the next section, the reader is already informed here that chosen is for Lithium-Ion batteries due to its modeling easiness and because of the current lack of literature on using Lithium-Ion batteries for battery-electric AGVs; most studies on battery-electric AGVs consider the more mature Lead-Acid batteries only. Because Lithium-Ion batteries have a substantially higher energy density, battery constraints may possibly be ignored when deploying electric AGVs at container terminals.
Finally, it has to be addressed that batteries need a thermal management system for heating and cooling of the battery to stay within the operating temperature interval. Cho et al. (2016) found that heating an electric vehicle's battery under an ambient temperature of -10 degrees Celsius, with which most considered batteries in Table 3.3 need heating, consumes about 15% of the total battery energy; for cooling, similar values are observed (Miller, 2010; Suh et al., 2015). However, information provided by VDL experts (see Appendix J) on their AGV battery thermal management system shows that this energy consumption is about 1% of the total consumption, thus implying that extreme temperatures are very rare in the Netherlands.

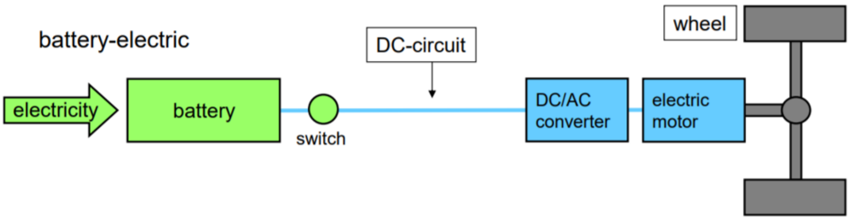


Figure 3.3: Main components of a battery-electric AGV (Terex, 2013)

3.1.2. Energy consumption of diesel and battery-electric AGVs

Van Duin and Geerlings (2011) performed research on the energy consumption of diesel AGVs driving at container terminals. They found that these AGVs consume 1.80 liters per loaded kilometer, i.e. when driving with a container on top; this value is very close to the number found by analyzing ECT AGV data regarding energy consumption of its diesel AGV fleet: 1.71 liters per loaded kilometer (see Figure 3.4). For empty AGV rides, however, neither literature nor data is available; therefore, back-of-the-envelope calculations are performed. ECT's AGVs have a dead body weight of 27.5 tons, a container weighs on average 17.5 tons (Teuwen, 2009). During a full trip, AGVs go through three states: *acceleration*, *constant speed* and *deceleration*. In each of these three states, AGVs experience either air resistance, rolling resistance or inertia resistance, a force which occurs due to a change in a vehicle's velocity, either a change of speed or a change of motion direction. Table 3.1 shows the magnitude of the resistances that occur in each of the three states, calculated by Teuwen (2009). The formulas are as follows:

$$F_{roll} = c * N \tag{3.2}$$

where:

$$c = 0.005 + (1/p) * (0.01 + 0.0095 * (v/100)^2 \tag{3.3}$$

$$N = m * g \tag{3.4}$$

$$F_{air} = 0.5 * \rho * c * A * v^2 \tag{3.5}$$

$$F_{inertia} = m * a \tag{3.6}$$

The total resistance is calculated as:

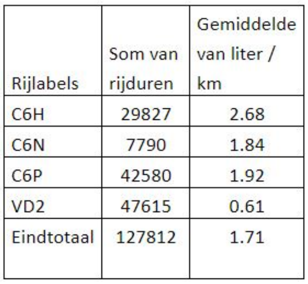
$$F_{total} = F_{roll} + F_{air} + F_{inertia} \tag{3.7}$$

Consequently, the power needed to drive the AGV engines is equal to:

$$P_{total} = F_{total} * v * \eta_{total} \tag{3.8}$$

The total energy consumption is calculated as:

$$E = P_{total} * t \tag{3.9}$$



Rijlabels	Som van rijduren	Gemiddelde van liter / km
C6H	29827	2.68
C6N	7790	1.84
C6P	42580	1.92
VD2	47615	0.61
Eindtotaal	127812	1.71

Figure 3.4: Average diesel consumption of ECT's diesel AGV fleet, calculated by dividing the total fuel used within three months by the total distance covered within these months

Table 3.1: Magnitudes of resistances per AGV state as calculated by Teuwen (2009)

	Acceleration	Constant speed	Deceleration
F_{roll} [kN]	12.88	12.88	12.88
F_{air} [kN]	0.73	0.73	0.73
$F_{inertia}$ [kN]	43.75	0.00	0.00

For the remainder of the calculations, one important assumption is made: the mass m is linearly related to the total power needed and, consequently, total energy consumed. This is reasoned by the fact that the air resistance has a very small share in the total resistance for all three states, as is observed in Table 3.1. This sounds logical as air resistance is mostly influenced by the speed of the vehicle; since AGVs drive 4 m/s at their maximum speed, this counter force is very small. Looking at the other two resistances, the mass m is linearly related to the total resistance covered by an AGV.

All the aforementioned information is used to calculate the energy consumption of empty AGV rides per kilometer. Since the mass is assumed to be linearly related to the total energy needed, the energy consumption of empty diesel AGVs in liters per kilometer is equal to:

$$\frac{27.5}{27.5 + 17.5} * 1.80 = 1.10 \tag{3.10}$$

For battery-electric AGVs, the energy efficiency is set at 66%, as obtained from section 3.1.1. This efficiency is:

$$\frac{0.66}{0.26} = 2.54 \tag{3.11}$$

times higher than diesel AGV's total energy efficiency. Knowing that (Connekt, n.d.):

$$1\text{liter diesel} = 10\text{kWh} \tag{3.12}$$

the total energy consumption in kWh/km of battery-electric AGVs without a container on top equals:

$$\frac{1.10\text{l/km} * 10\text{kWh/l}}{2.54} = 4.33 \tag{3.13}$$

For loaded battery-electric AGVs, the energy consumption in kWh/km is equal to:

$$\frac{1.80\text{l/km} * 10\text{kWh/l}}{2.54} = 7.09 \tag{3.14}$$

Table 3.2 provides an overview of the energy consumptions of both diesel and battery-electric AGVs which will be used as input into the simulation model regarding AGV driving performance and into the total costs of ownership analysis regarding fueling costs.

Table 3.2: Overview of diesel and battery-electric AGV's energy consumptions

	Diesel AGV	Electric AGV
Empty [kWh/km]	11	4.33
Loaded [kWh/km]	18	7.09

3.2. Vehicle batteries

Electric batteries have specific characteristics which are important to address in the context of electric AGVs being deployed at container terminals. Khaligh and Li (2010), Thomas (2009a) and Battery University (2018a) mention *specific energy*, *specific power* and *cycle life* as most important properties. Specific energy is the energy that can maximally be stored per unit mass, often expressed in *Watt*hour per kilogram* (Wh/kg). Specific power, also known as power-to-weight ratio, is the maximum power that can be generated per unit mass, most often operationalized in *Watt per kilogram* (W/kg). The cycle life describes the number of times a battery can be *fully discharged* from being fully charged until the battery capacity falls under 80% of the original capacity and has to be replaced (Battery University, 2018g). This last characteristic is dependent on the *Depth of Discharge* (DoD) of the battery, which is defined as "the capacity that is discharged from a fully charged battery divided by the nominal capacity of that battery" (Battery University, 2018e). Kooten Niekerk et al. (2017) graphically shows the relation between average DoD and battery lifetime for Lithium-Ion batteries. By calibrating parameters of a mathematical function to a typical DoD-lifespan curve, they found the relation as shown in Figure 3.5; high DoDs result in exponentially less charging cycles, which should thus be minimized as much as possible. Opportunity charging seems particularly suited for this objective as instead of fully discharging, the battery is being charged more frequent within tighter battery level intervals, thereby reducing the probability of full DoDs. Non-linearity can also be observed when looking at the charging curve of batteries (Figure 3.6). Until 80% of the battery capacity, there is a linear increase in electric energy level with increasing charging time. After 80%, the curve becomes flatter in order to avoid overheating of the battery (Battery University, 2018d). More technically speaking, the C-rate for batteries is set such that after 80% State of Charge the receptiveness of the battery starts to drop, yielding a lower C-rate (Battery University, 2017b). Kooten Niekerk et al. (2017) state that charging the battery from 80% to 100% takes approximately the same time as charging from 0% to 80%. Typically, fast charging is applied for the linear part after which slow or conventional charging completes the residual 20%.

3.2.1. Battery technology variation

Literature on batteries for electric vehicles mostly cover five technologies (Battery University, 2018a; Khaligh and Li, 2010): *Lead-Acid*, *Nickel-Cadmium*, *Nickel Metal Hydride*, *Nickel-Zinc* and *Lithium-Ion*. Lead-Acid batteries have been widely applied as starting engines for cars over the past 50 years due to their ability of delivering high currents in short times (Khaligh and Li, 2010). Also, its low price and ease of composition make Lead-Acid a favoured option, as can be derived from APM Terminal's recent choice for this type of batteries for their 62 Lift-AGVs at Maasvlakte II (APM Terminals, 2015; Verdonk, 2013). Main downsides of Lead-Acid batteries are their low energy and power density which result in very heavy battery packs, the long charging time which can count up to 14-16 hours and the toxicity of main materials when disposed after their lifetime (Battery University, 2018a). Nickel-Cadmium batteries have also been in the field for more than 50 years with wide applications in portable devices until the 1990s (Battery University, 2018b). Main advantages of this battery are the long lifetime in terms of charging cycles, corresponding relatively low costs per cycle and its tolerance for deep discharge cycles without reducing the battery lifetime (Battery University, 2018b; Khaligh and Li, 2010). Also, the specific power of Nickel-Cadmium batteries is higher when compared to Lead-Acid batteries. Main downsides, though, are the high investment costs (more than 20,000 dollars for installment in vehicles) and the use of Cadmium, which is environmental unfriendly (Battery University, 2018a; Khaligh and

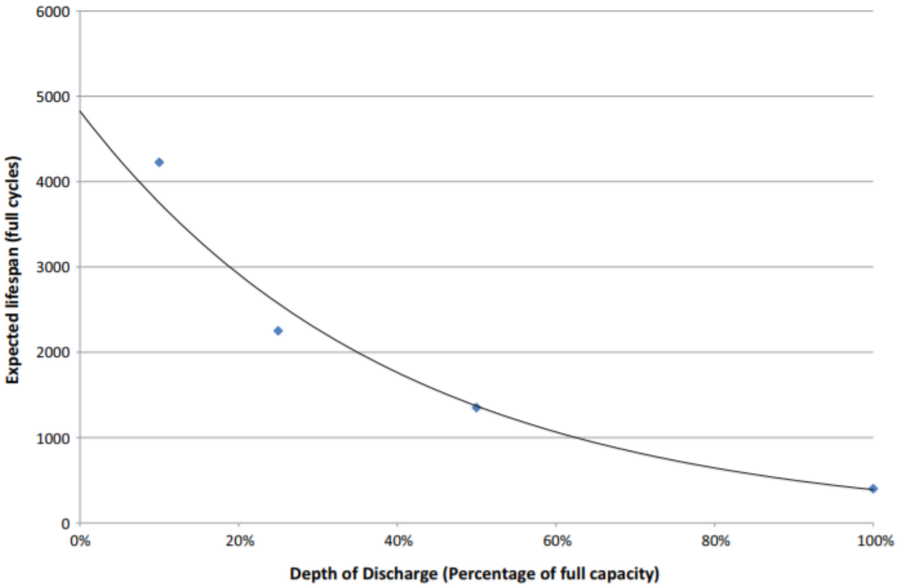


Figure 3.5: Graphical relation between DoD and lifetime

Li, 2010). Nickel Metal Hydride batteries have a 30-40% higher capacity than their Cadmium counterparts, have twice as large energy density as Lead-Acid batteries and are environmental friendly, but on the other side these batteries are sensitive to high DoDs which can reduce the lifetime with 200-300 cycles and they generate heat when being fast charged, which increases the risk of fire (Battery University, 2018b; Khaligh and Li, 2010). Nickel-Zinc batteries have an extremely high specific power, high specific energy, are cheap and environmental friendly but have not been widely applied in the vehicular field because of the increased risk of electrical shorts due to dendrite growth. However, recent improvements have reduced dendrite growth which makes Nickel-Zinc batteries available again for commmercial purposes (Battery University, 2018b). Finally, the most promising battery technology for electric AGVs is Lithium-Ion which is the lightest of all discussed batteries, have the highest specific energy, high specific power, long lifetime (1000 cycles), short charging times and good performance at high temperatures. Also, Lithium-Ion batteries are recyclable. Their main disadvantages are the reduction in lifetime when deeply discharged, i.e. deeper than 20% of the battery capacity, or operating at high temperatures and the higher costs when compared to the other battery technologies (Battery University, 2018c). Table 3.3 gives an overview of all discussed batteries considering main characteristics, advantages and disadvantages.

Table 3.3: Characteristics of the five most promising battery types (Battery University, 2018a; Battery University, 2018b; Battery University, 2018c; Dhar et al., 1997; Khaligh and Li, 2010)

	Lead-Acid	**Nickel-Cadmium**	**Nickel metal Hydride**	**Nickel-Zinc**	**Lithium-Ion**
Specific energy [Wh/kg]	40	50	100	100	200
Energy density [Wh/L]	80	100	200	280	500
Specific power [W/kg]	180	150	750	3000	300
Cycle lifetime [# cycles]	200 - 500	1000	400	100	1000
Charging time [h]	8 - 16	1 - 2	2 - 4	2 - 3	1 - 2
Operating temperature [°C]	-20 - 50	0 - 45	0 - 45	0 - 45	0 - 45
Costs [€/kWh]	150	300 - 600	300 - 600	300 - 600	500 - 1000
Environmental friendliness	-	-	+	+	+
Insensitivity to high DoD	+	+	-	-	+/-
Maintenance required [months]	3-6	3	3	3	n.a.

3.2.2. Battery choice for this research: Lithium-Ion

Looking at Table 3.3, it is observed that regarding operational performance Lithium-Ion batteries score by far better than the other technologies. However, considering costs Lithium-Ion batteries prove to be more

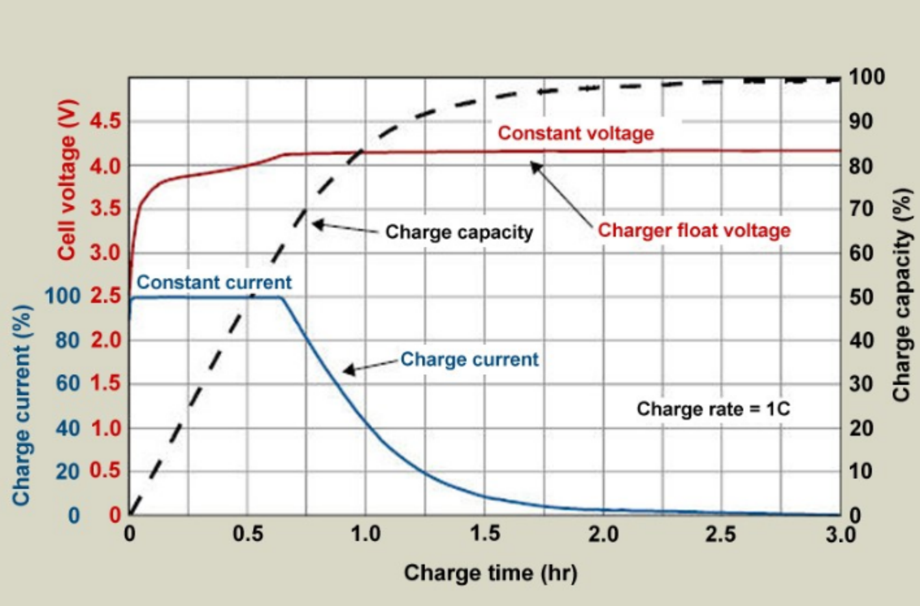


Figure 3.6: Battery charging curve

expensive. A trade-off between operations and costs should thus be made in order to select a battery type. Since the focus of this research is not on the impact of using different battery technologies on AGV operational performance but merely on the operational feasibility of battery-electric AGVs in general, this trade-off is out of scope of this research. It is decided to choose Lithium-Ion batteries for the remainder of this Thesis study. This decision is reasoned twofold:

1. As there has been conducted research already on the operational and financial impact of deploying Lead-Acid and Nickel-based battery-electric AGVs (McHaney, 1995; Schmidt et al., 2014; Schmidt et al., 2015), no research has been performed yet on using the most promising battery technology, Lithium-Ion batteries. By using Lithium-Ion as technology, battery constraints may potentially be ignored. This research therefore aims at filling this current knowledge gap in literature.

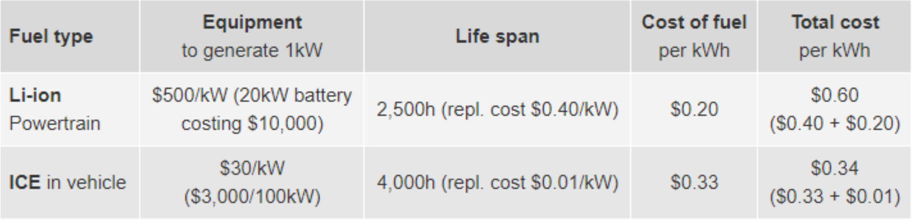
2. Summarizing the literature on battery-electric AGV's efficiency and DoD and charging time of batteries, Lithium-Ion turned out to be most reviewed. In fact, the observation by Kooten Niekerk et al. (2017) that charging a battery from 0 to 80% takes approximately equal time as charging from 80 to 100% applies to Lithium-Ion batteries only. For Nickel- and Lead-based batteries, the charging curves are more complex and are therefore not suited for this study. For these two reasons, the choice is made for Lithium-Ion batteries.

For the remainder of this study, however, Lithium-Ion batteries are considered only on the condition that high DoDs are being avoided. This means that Lithium-Ion battery-electric AGVs always must go charging whenever their battery level has dropped below 20% (obtained from section 3.2.1).

3.2.3. Battery sizing

The wide deployment of electric vehicles is hampered due to several factors, of which two of the most important, mentioned in many articles, are *costs* and *driving range* (Boulanger et al., 2011; Cairns and Albertus, 2010). Considering the state-of-the-art in battery and internal combustion engine (ICE) technology, an economic analysis conducted by Battery University (2017a) and Brennan and Barder (2016) shows that batteries for electric vehicles are almost twice as expensive as ICEs, taking into account investment, maintenance, replacement and fuel costs. These high battery costs take a significant share in the total vehicle costs; although it is expected to drop due to *economies of scale* and *learning effects*, still almost half of the vehicle costs (43%) is covered by the battery (Statista, 2018).

Hu et al. (2013) investigated a potential remedy to this high cost share in a conventional bus set-up: battery downsizing, which fundamentally reflects varying the volume and weight of a battery in order to find



Fuel type	Equipment to generate 1kW	Life span	Cost of fuel per kWh	Total cost per kWh
Li-ion Powertrain	$500/kW (20kW battery costing $10,000)	2,500h (repl. cost $0.40/kW)	$0.20	$0.60 ($0.40 + $0.20)
ICE in vehicle	$30/kW ($3,000/100kW)	4,000h (repl. cost $0.01/kW)	$0.33	$0.34 ($0.33 + $0.01)

Figure 3.7: Total cost of ownership comparison ICEs and batteries (Battery University, 2017a)

an optimal weight/volume ratio for a specific transport purpose. Heavy battery packs are able to store more energy, however, due to the increased weight a smaller part is converted into actual movement of the vehicle, thereby affecting the energy efficiency. Smaller battery packs, on the other side, lead to a degradation in fuel-to-traction and recuperation efficiency, of which recuperation is an important energy collecting mechanism for battery-electric vehicles (Hu et al., 2013). In the case of fully electric AGVs at container terminals, large energy storage capacities, with Lithium-ion battery weights of Kalmar and VDL counting up to 4 to 5 tons with 180 kWh capacity (see Appendix J for the reference) and Lead-Acid batteries of APMT weighing 11.5 tons with a capacity of 360 kWh (Machinebouw, 2013), are most probably not needed because of the short driving distances AGVs travel between the QC and ASC, combined with potential frequent charging in the loop due to high AGV waiting and idle times. However, an increase in the number of start-stops, combined with the heavy load AGVs must be able to carry (up to 70 tons), could compensate shorter travel distances with higher required specific power, thereby limiting the potential of battery downsizing. To conclude, a trade-off must be made between battery size, in terms of weight and volume, and energy efficiency, which still seems to be an open research gap in literature. Yet, battery sizing tends to correlate with the speed of charging as fast charging allows the vehicle battery to be smaller (Botsford and Szczepanek, 2009). Implications for this study are, as will be elaborated upon further in Chapter 6, to vary the battery capacity of electric AGVs in order to investigate which capacity leads to operational and financial feasibility for terminal operators.

3.3. Charging techniques and strategies

The main challenge of battery-electric AGVs at deep sea container terminals is the *way of charging*, which includes both the physical method of charging (i.e. how to charge) as well as the strategy with which this method is deployed for the entire AGV fleet (i.e. when to charge). Both aspects are considered and used as input into the generation of designs of the future AGV charging process in Chapter 4.

Before reviewing the dominant physical charging methods, the levels of charging which became standard for electric vehicles are discussed. While Level 1 charging comprises charging at home or overnight charging through a 230 Volt standard household outlet, Level 2 charging offers charging at 240 Volt and Level 3 even at 450 V (50-100 kW power level), guaranteeing normal vehicles to be charged 80% within 30 minutes (Yilmaz and Krein, 2013). Though, this power level is still too low to charge AGVs sufficiently within the given time frame: documentation of Kalmar, ZPMC, Konecranes/Gottwald and Heliox reveals a required power level varying from 250 kW to 450 kW to charge AGVs fully within an hour (Heliox, 2018; Kalmar, 2018; ZPMC, 2018). Therefore, the standardized levels of charging do not apply to battery-electric AGVs. For the remainder of the literature study, relevant charging data is also retrieved from the field of electric buses; in terms of size, AGVs approach these types of vehicles more than private ones. Still, the driving behaviour remains fundamentally different: whereas buses are characterized by long traveling distances, short waiting times and interruptions in the transport process during night, AGVs mostly travel short distances, face high waiting times per transport cycle (see section 2.4) and must be available 24/7. Also, AGVs must be able to carry cargo with weights up to 70 tons while the loading capacity of buses reaches 30 tons at most (VDL, 2018b). Finally, buses are equipped with a heating and cooling system in order to guarantee a comfortable temperature for its passengers; obviously, for AGVs this is not necessary.

3.3.1. Charging techniques: how to charge

Considering charging methods, the most used charging type for electric vehicles is *plug-in*, where a cord, connected to the electricity grid, manually or automatically charges the vehicle in case. The power delivered depends on both the output power from the charger and the delivery power rate of the battery; whoever's power is lowest 'wins' and sets the default power rate for the battery to be charged. In consultation with experts from quick charger manufacturer Heliox (see Appendix J), AGV batteries have a C-rate of 3-5 C which means that a battery with a capacity of 160 kWh can maximally be charged with a charging power of 5*160 kWh = 800 kW.

Electric AGV supplier Kalmar has offered this type of AGVs to the Port of Singapore PSA, offering a quick charger with a power of 300 kW, guaranteeing 4 hours operation time within 30 minutes of charging (Kalmar, 2018). Figure 3.8 shows the Kalmar plug-in AGV; the costs of a quick charging unit is 200,000 euros. Dutch quick charge supplier Heliox offers plug-in chargers with an output power of 600 kW, promising an automatic coupling time of 10 seconds with the AGV (Heliox, 2018). The price of one charging unit also equals 200,000 euros, excluding the construction costs of the underlying power grid. Finally, Stäubli quick charge supplier offers plug-in chargers in the range of 350-600 kW (Stäubli, 2018). All of the above mentioned plug-in charge suppliers guarantee efficiency rates of more than 95%, with Heliox even promising a 97% charging efficiency.

A second charging technique which is widespread under terminal operators is *battery swapping*. Battery swapping covers the exchange of drained batteries with (fully) loaded ones and the charging of drained batteries. As mentioned earlier, ECT's neighbours APM and RWG use this method for charging their AGV fleet. Konecranes/Gottwald, one of the most prominent electric AGV manufacturers, provided these battery swap stations to both terminals; they promise a battery swap time of approximately 5 minutes; APM terminals observes a similar swap duration of their Lead-Acid batteries (Verdonk, 2013). Due to the expensive physical infrastructure needed - large, well ventilated exchange stations and a certain amount of spare batteries for redundancy - and the recurrent maintenance on this infrastructure, battery swapping as charging technique can lead to very high costs. Fang et al. (2017) performed research on the total costs of battery swapping stations for electric buses: only incorporating the number of (spare) batteries, number of chargers, electricity costs and other battery swap equipment sums up to a total of more than 19 million Taiwanese dollars, approximately 550,000 euros; Shao et al. (2017) found a total cost of 350,000 euros. On the other side, battery swapping stations provide a very high charging efficiency due to the external charging of batteries. This also enables the spare batteries to be slowly charged, thereby reducing stress caused by quick chargers (Battery University, 2018d).

A third charging technique which is currently receiving more attention in the field of electric buses and electric straddle carriers is *pantograph charging*. A pantograph is an object installed at either the roof or bottom of an electric transport modality which collects electric energy through a four pole contact with the electric grid (Siemens, n.d.). On-vehicle and inverted pantographs can be distinguished: whereas on-vehicle pantographs require continuous overhead lines, similar to the tram and rail network, inverted pantographs only require a small rail on the top or bottom of the vehicle which makes contact with a pantograph installed on a fixed location. Figure 3.9 shows the concept of inverted pantograph charging. The latter one obviously is less costly due to the absence of a large overhead electricity network; only a contact point (e.g. a rail) and

Figure 3.8: Kalmar FastCharge AGV Plug-in

fixed pantograph locations are needed. On-vehicle pantograph charging rises to more than approximately 650,000 euros per route kilometer, including installation of the overhead line and pantograph costs (Keen et al., 2010). Inverted pantograph charging, on the other side, costs around 300,000 euros (Hornby, 2017). Several bus companies all over the world make use of an inverted pantograph for opportunity charging at bus stops (Markusik et al., 2015; Nuiten, n.d. Siemens, n.d.). For port equipment, pantograph charging is rarely observable in practice; one of the few examples is Kalmar's FastCharge Straddle Carrier, which is depicted in Figure 3.10. This inverted pantograph system delivers power up to 600 kW to the straddle carrier via a collector on top of the shuttle, promising a full charge time of 5 minutes (Kalmar, 2016; Kalmar, 2018). Application of inverted pantograph charging to electric AGVs is not realized yet due to the way these vehicles are being used: as containers are carried on top of the AGV, roof-mounted inverted pantograph charging is not possible due to conflicts during container (un)loading and transport. However, inverted pantographs installed on the ground or sideways which make contact with the AGV could be an option from a functional perspective, assuming that there is enough space on the vehicle for contact with the pantograph system. The rated power efficiency, as stated by various pantograph system suppliers, is more than 96%, with the Siemens E-bus even guaranteeing a 99% efficiency (Heliox, 2018; Siemens, n.d.).

Closely related to pantograph charging is *rail charging*, which charges vehicles by connecting them to a rail which is connected to an electric grid (Viktoria, 2014). Pantographs could for example be used as in-vehicle collectors of electric energy, serving as an alternative to the roof-mounted installation discussed with the previous technique. Instead of an overhead line, rails installed on the ground charge crossing vehicles along their way, as is the case on a Sweden road stretch used by electric cars (Guardian, n.d.). Main advantage is the possibility of charging while driving, enabling in-motion charging of vehicles. Costs per kilometer rail are believed

Figure 3.9: Concept of pantograph charging

Figure 3.10: Kalmar FastCharge Straddle Carrier

to equal 1,000,000 euros, excluding the charger installation costs on the vehicles. According to the institution Viktoria Swedish ICT, closely related to the installation and implementation of the rail-charging Swedish road stretch, energy efficiencies reach, with a nominal power of 103 kW, 96.9% (Viktoria, 2014). Though, the supplied power can be upgraded to 120 kW. The supplied voltage to the rail charging system is in the order of magnitude of 750 V DC (Bartłomiejczyk, 2017; Viktoria, 2014). A critical note is that the rail system must be free of snow and ice in order to function properly, which may be problematic during the winter months, especially at container terminals located at the coast.

The last charging technique to be discussed is *inductive charging*, which resembles "the wireless charging of vehicles by using an electromagnetic field to transfer energy to a vehicle through electromagnetic induction" (Wu et al., 2011). By producing high frequency alternating currents in a transmitter coil, electric power is inductively transferred to the receiving coil in the vehicle, which converts the alternating current into direct current, suitable for charging batteries. Induction charging has several advantages over wired charging: whereas wired charging may need manual assistance, wireless inductive charging operates fully automatically from the moment a vehicle begins to occupy the inductive plate, making the charging process safer for employees (Lukic and Pantic, 2013). Also, inductive charging has no start-up time, where the plug, pantograph or other energy collector has to make contact with the energy supplier, thereby reserving more time for actual charging the battery. Furthermore, induction charging requires relatively less maintenance than their wired counterparts due to less movement, and thus less friction, of parts (Lukic and Pantic, 2013). Finally, inductive charging enables vehicles to be charged while driving, similar to rail charging (although rail charging still requires physical contact). However, there are also some important downsides of inductive charging when compared to conductive and wired charging. First, the charging efficiency is considerably lower due to the in-vehicle conversion of AC to DC, which inevitably results in energy loss. Khaligh and Dusmez (2012) report an efficiency rate of 90-93%, while Lukic and Pantic (2013) and Bi et al. (2015) mention an efficiency rate of 85-90%. Second, inductive charging causes magnetic emissions which may also conflict with communication systems (Lukic and Pantic, 2013); e.g., from a practical point of view, inductive charging at the ECT Delta Terminal may conflict with the AGV-TOS communication system, which is highly undesirable (Middelburg and Boer, 2017). As the AGVs are unmanned, important driving information is collected from this TOS, where a lack of communication may lead to collisions between AGVs and interruptions in the transport process. Third, inductive charging requires very precise positioning of the vehicles on the inductive plate in order to make contact with the supplier coil (Khaligh and Dusmez, 2012). The efficiency of the transfer of energy decreases substantially with increasing disarrangement of the supplying and receiving coils (Loewel et al., 2013). A pilot *Wireless charging* held in Rotterdam reported a decrease in efficiency from 90% to 70% when the vehicle was driving during charging (Elfrink et al., n.d.). However, vehicle displacement during static charging also affects the power efficiency, though, with AGVs having a positioning accuracy of 3 centimeters this disarrangement is not expected when standing still (Middelburg and Boer, 2017). Also, the vertical distance between the two coils mostly determines the charging efficiency: Kerkhof and Sloten (2014a), Elfrink et al. (n.d.) and Lu et al. (2016) all concluded that a vertical distance of maximum 20 centimeters results in the highest charging efficiency of around 90%. Higher vertical distances could decrease this efficiency with 10-15%. Regarding costs, installing the supplier coil into the pavement costs around 120,000 euros and installment costs of the receiving coil into the vehicle are about 16,000 euros, considering the deployment of electric buses in Torino, Italy (Eltis, 2015). Yet, it must be noted that the provided charging power for these buses is 65 kW, while quick charging AGVs requires far more power, in the order of magnitude of 200-300 kW (Teuwen, 2009). As a consequence, costs are expected to turn out much higher for higher power needs, where inductive charging power for heavier transport currently reaches 200 kW at most (Kerkhof and Sloten, 2014b). For in-motion charging, installation costs reach 300,000 to 500,000 euros per kilometer (Kerkhof and Sloten, 2014a).

3.3.2. Charging strategies: when to charge

The charging techniques discussed in the previous section can be deployed and managed in various ways. McHaney (1995) already listed three charging schemes to be used for multi-AGV systems: automatic charging, in which AGVs with low level batteries are assigned for charging at an external location, opportunity charging, which uses AGV's idle times to charge the battery, and a combination of opportunity and automatic charging. Looking at the literature on charging of electric buses and other vehicles in a logistic setting, Teoh et al. (2016) defined four charging strategies in an urban logistics setting: *overnight* charging, *break time* charging, charging *during loading and unloading* and charging *on the highways.* Comparing these strategies to a water side terminal operation setting, overnight charging is simply not possible due to the 24 hours operating time of AGVs. Although break times are observable throughout the day, they are the result of a change in shift of the QC operators rather than actual break or lunch times. Therefore, these break times are tried to be minimized as much as possible to ensure continuous operation. The third strategy, charging during loading and unloading, seems well suited for AGVs at container terminals since container (un)loading is an essential part of the transport process (see Figure 2.5). Moreover, since (un)loading operations take up a considerable amount of time in the total AGV transport cycle as can be retrieved from Figure 2.8 and Table 2.1, the opportunity arises for charging during loading and unloading. Charging on the highways, considering an urban setting, can be translated into in-motion charging of AGVs while driving to the QC or ASC. Inductive and rail charging are suited for this charging strategy because of their ability to dynamically charge vehicles (Guardian, n.d. Lukic and Pantic, 2013).

Instead of looking at the opportunities for charging, the pace at which charging is being performed can be either *slow* or *quick* (Botsford and Szczepanek, 2009; Elin, 2016). Slow charging is characterized by low power and is mostly used for overnight charging or when vehicles are expected to be idle for longer periods of time. Plug-in, inverted pantograph and fixed-location inductive charging at low voltages are the most obvious options for this type of charging; rail charging, dynamic inductive charging and battery swapping are not considered viable options because of the high investment costs while cheaper alternatives (e.g. plug-in) are available with equal or even higher efficiencies. Quick charging, on the other hand, delivers (very) high power in short periods of time and is suited for rapid charging at logistically strategic locations. Due to operational constraints, expensive alternatives may be favoured over others. For example, APM terminals uses battery swapping stations at the corners of the terminal to fully charge their AGV fleet. Moreover, plug-in, pantograph, inductive and rail charging can be used as quick charging technique because of their high power delivery.

A last distinction can be made between *static* and *in-motion* or dynamic charging (Karakitsios et al., 2016). Whereas static charging charges the vehicle at a fixed location, in-motion charging loads the vehicle's battery along the route. Plug-in, pantograph and inductive charging and battery swapping can be statically applied, while on-vehicle pantograph, rail and dynamic inductive charging can charge the vehicle in-motion. The distinctions in both static-dynamic and slow-quick charging result in the charging classification as depicted in Table 3.4.

3.4. Conclusion

This chapter aimed at providing the reader the state-of-the-art in charging battery-electric AGVs at container terminals in order to be used as input into the design of the future AGV charging process in Chapter 4 and the operational comparison of diesel and battery-electric AGVs in Chapter 6. Started is with a comparison of the energy efficiency and energy consumption of diesel and battery-electric AGVs using both ECT data and back-of-the-envelope calculations. Using formulas 3.2-3.9, it is obtained that ECT's current diesel AGV fleet consumes 1.80 liters/kilometer when loaded with a container on top, while 1.10 liters/kilometer is being consumed when driving empty. Having calculated the well-to-wheel efficiency of a Lithium-Ion battery of 66%, it is deducted that battery-electric AGVs consume on average 4.33 kWh/kilometer when driving empty, while consuming 7.09 kWh/kilometer when driving with a container on top. Consequently, these values are used as input into the developed simulation model.

Next to energy consumption, battery characteristics have also been reviewed in order to be used for simulating battery-electric AGV charging. Most important to mention are:

- non-linearity of a battery's charging curve; instead of a linear increase in electric energy during charging, Kooten Niekerk et al. (2017) state that batteries are charged linearly until 80% of its capacity. After this, slow charging with a lower current is applied for the remaining 20%; Kooten Niekerk et al. (2017) consider both charging times (0-80% and 80-100%) to be equal, which will also be applied in the simulation model.

- relation between deep battery discharges and lifetime. Structural deep discharges, over 80%, cause battery damage which must be avoided. Opportunity charging seems to be particularly suited for this purpose as tighter battery level intervals can be managed, e.g. between 40% and 80%.

Regarding the choice of batteries for this research, Lithium-ion has been chosen for the sake of its (1) representative literature, (2) current lack of research and (3) its potential for 24/7 continuous use at container terminals due to its high energy density. Considering the size of the batteries, from literature it is observed that this is an important factor to vary as larger batteries deteriorate energy efficiency while smaller batteries pose risks for vehicle availability: a trade-off must therefore be made.

Having discussed the vehicle and batteries, the actual charging, both physical (how) and strategical (when), to be deployed at container terminals has been investigated by means of a literature research; the main findings are synthesized in Table 3.4.

The main output of this chapter is twofold: the driving performances of diesel and battery-electric AGVs are used as input into the simulation study and total costs of ownership analysis performed in Chapters 6 and 7, where driving characteristics in terms of energy use differ between the vehicle types and thus affect both operations and costs. Regarding the battery choice and characteristics, this will also be used as input into the simulation study to serve two purposes: Lithium-Ion determines the driving performance in terms of energy density, while the charging non-linearity determines the charging time of the battery-electric AGVs. Finally, the synthesized charging techniques, strategies and characteristics are used as input into the generation and evaluation of designs of the future AGV charging process in the next chapter.

Table 3.4: Literature synthesis of how and where to charge

			Charging location at terminal	Charging power [kW]	Charging efficiency [%]	Infrastructure costs [€]	Advantages	Disadvantages
Static	**Slow**	Plug-in	ASC TP, edge of AGV area	Up to 90	95-97	50,000 excluding connecting power grid	Easily maintanable, wide variety of suppliers	Sensitive to wear, (un)coupling time needed
		Inverted pantograph		22-100	96-99	50,000	Flexible vehicle positioning	Sensitive to wear, (un)coupling time needed
		Inductive		30-120	85-90	100,000-140,000	Less maintenance needed, immediate charging, fully automated	Lower efficiency than other techniques, magnetic emission, very precise positioning needed
	Quick	Plug-in	ASC TP, QC lane, edge of AGV area	250-600	95-97	200,000	see above	see above
		Inverted pantograph		450-650	95-99	300,000	see above	see above
		Inductive		120-200	85-90	100,000-140,000	see above	see above
		Battery swapping	Edge of AGV area	n.a.	99-100	350,000-550,000	Very quick swap time (5 minutes), stress reduction on batteries	Very expensive, much space required
In-motion	**Slow**	n.a.						
	Quick	On-vehicle pantograph	Dedicated lanes on AGV grid, QC lane	450-650	97	400,000-650,000 per kilometer	No interruption in transport process	Very expensive, fixed route
		Rail		103-120	97	1,000,000 per kilometer (only one news source available)	No interruption in transport process	Very expensive, fixed route, sensitive to adverse weather conditions and wear
		Inductive	Dedicated lanes on AGV grid, QC lane, practically everywhere along the AGV grid	50-250	70-80	300,000-500,000 per kilometer	No interruption in transport process	Even lower efficiency, conflict with communication systems

4

Designing the future AGV charging process

This chapter aims to answer the third subquestion,
3. Which design of the AGV charging process can be selected for further evaluation based on brownfield terminal operator's requirements and constraints?
by summarizing the main findings of the current AGV operations and the state-of-the-art in electric AGVs, batteries and charging techniques in sections 4.1 and 4.2. These findings are subsequently used as input into this chapter. By interviewing this study's problem owner, main design requirements and constraints for the final designs are identified in section 4.3. In this section, the system to be designed, the AGV charging process, is also functionally decomposed in order to trawl alternatives for each system function by means of a morphological chart in section 4.4. Based on this morphological chart and the identified design requirements and constraints, the most promising design is selected in sections 4.5 and 4.6 for further evaluation in the next chapters of this study. Figure 4.1 graphically shows the structure of this chapter with the main output and relations between the sections.

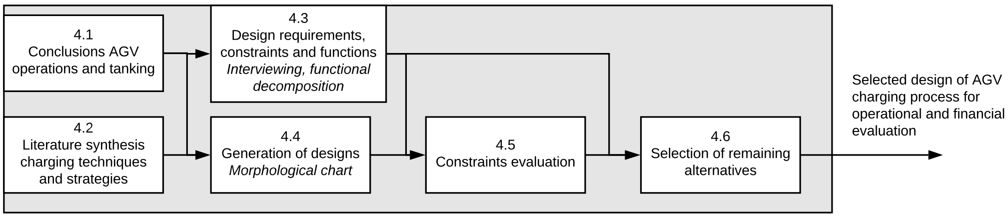


Figure 4.1: Structure, methods and output of Chapter 4

4.1. Conclusions from current diesel AGV operations and tanking

For the design of the future AGV charging process, the current AGV operational and tanking processes, the only two processes considered in this study, are quickly summarized as this is used as input into the design. Regarding the operational process, most of the time AGVs are either waiting at the ASC and QC TPs for their container to be (un)loaded by the ASCs and QCs, waiting at the ASC TPs until they get 'permission' from the TOS to start driving to the QC lane or idling at the ASC TPs in between two transport jobs. Looking at Figure 4.2, it is seen that most opportunity for battery charging occurs at the ASC TPs and to a lesser extent in the QC lane, given a total time of 45 minutes in between the start of two subsequent jobs for a single AGV.
Considering the tanking process, the decision logic is rather simple: in case an AGV's fuel load has dropped below 200 liters, AGVs receive a notification that they need to tank. However, the actual decision whether an AGV goes tanking is made by the TOS as this operating system is responsible for a proper progress of the container transport process. More specifically, by building in this slack of 200 liters it is avoided that diesel AGVs all go tanking at the same time. The second notification is sent when an AGV's fuel load has dropped below 100 liters. In general, 100 liter AGVs get priority over 200 liter notified AGVs. When the TOS assigns the AGV to a tanking spot at the edge of the operational area, the AGV starts driving to this tanking station

and gets its fuel load tanked until maximum, 1200 liters, within 5-10 minutes. From this tanking process, the main decisions to be made are *when* and *where* to tank while not affecting the operational process.

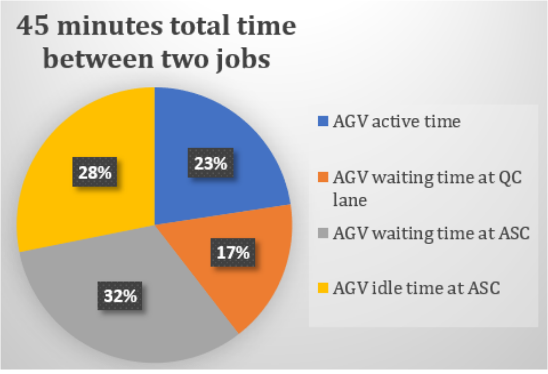


Figure 4.2: Total AGV time distribution in active, waiting and idle time

4.2. Literature synthesis on charging techniques and strategies

Whereas the current tanking process only takes into account when and where to tank - tanking spots are divided over the edges of the operational area for redundancy - one crucial difference with future battery charging is the question *how to charge*. Chapter 3 aimed at synthesizing the current state-of-the-art on how to charge by synthesizing and evaluating the current charging techniques available on the market in Table 3.4. This synthesis, together with the conclusions from the AGV operational and tanking process, is consequently used as input into the remainder of this chapter.

4.3. Identification of design requirements, constraints and system functions

Identifying a problem owner's main objectives sounds trivial but turns out to be an art in itself. Sage and Armstrong (2000) advise in their *Introduction to Systems Engineering* handbook to classify objectives based on a variety of categories inspired by Hall (1962), of which cost, quality, performance, reliability, compatibility, safety, simplicity and time objectives are most applicable to electric charging of AGVs at container terminals. Bahill and Madni (2017) make a distinction between functional and non-functional requirements, where functional requirements define "what, how well and under what conditions one or more inputs must be converted into one or more outputs in order to satisfy the customer's needs". Non-functional requirements describe the attributes that the system must have and are closely related to the main objectives of the problem owner. In fact, by identifying non-functional requirements, one can determine a problem owner's main objectives and vice versa. When further operationalizing these requirements in measurable quantities, design criteria can be obtained on which generated charging designs can be assessed. On the contrary, starting with the identification of main objectives, one can derive important system functions future charging designs must comply with (Sage and Armstrong, 2000). System functions describe what the system must do or accomplish and are useful for identifying functional and non-functional requirements. Finally, constraints indicate the limitations of a design, i.e. the boundaries of the design space which may not be violated (Sage and Armstrong, 2000).

In this study, started is with the identification of design requirements and constraints, after which the system to be designed, the AGV charging process, is decomposed into its most important system functions. Finally, the most promising alternative based on the design requirements and constraints is selected for further evaluation by means of simulation and a total costs of ownership analysis in the next chapters. However, before starting with the formulation of requirements and constraints, an insight into the stakeholder dynamics regarding battery-electric AGVs at the ECT Delta Terminal is given in order to enrich the eventual set of requirements and constraints future charging designs should comply with.

4.3.1. Stakeholder analysis

For this study, the problem owner in case is, as frequently mentioned, ECT. However regarding battery-electric AGVs, ECT can on its turn be subdivided into smaller departments with individual needs and objectives, which may conflict with each other. Having conducted several interviews with employees from various departments (see Appendix J for the references), the following stakeholder groups can be distinguished (for a stakeholder wide objective tree, the reader is referred to Appendix C):

- *Technical and Operational Department (TOD)*, which is currently responsible for maintenance activities on diesel AGVs. A fully electric vehicle fleet is expected to reduce maintenance costs significantly, as does APM Terminals observe with their battery-electric AGVs (Boyd and Tazelaar, 2012). On the one hand, this relieves the workload on TOD workers, so do zero-emission, zero-noise AGVs contribute to a more healthy labour environment. However, lower costs yield less maintenance workers needed, therefore, retraining in the direction of electrotechnical maintenance is required to maintain TOD satisfaction. Yet, it must be noted that a future growth of container transshipment will most likely compensate this decrease of dependency on maintenance employees.

- *Infrastructure and Equipment Department (I&E)*, who is responsible for the selection and purchase of electric AGVs, the infrastructural requirements and actual construction of water side charging facilities for these vehicles and for the maintenance of charging infrastructure. I&E strives for an optimal use of charging equipment that fits within the current terminal layout. Also, from their point of view it is preferred that the replacement of diesel infrastructure by a power grid for electric AGVs will take as little (and as cheap) replacement work as possible, so must future charging infrastructure not conflict with other terminal equipment, e.g. the ASCs, QCs and AGV communication system.

- *Logistical Department (LD)*, which controls the logistical flow at the water side terminal by assigning AGVs to containers to be handled and coordinating AGV, ASC and QC activities. From Chapter 2, it is recalled that LD opts for an AGV transport system which does not lead to a deterioriation in terminal performance.

- *Financial Department (FD)*, who manages ECT's financial resources. FD desires a transition from diesel to battery-electric AGVs that is as cost effective as possible, with as little future maintenance and energy costs as possible. Of crucial importance is the cost effectiveness on the long term, as low purchasing costs may result in high lifetime costs in the form of maintenance and vice versa. Furthermore, since electric AGVs are expected to have a lifetime of 20 years, while batteries quickly degrade after 10 years, it is of crucial importance that the well-functioning of battery-electric AGVs shall at least approach (and exceed) this lifetime (Kalmar, 2018). In this study, lifetime costs are explicitly taken into account by means of a total costs of ownership analysis because potential conflicts may arise between FD on the one side and the TOD and I&E on the other side regarding capital and operational investments in appropriate and innovative electric vehicles and infrastructure.

External stakeholders can be categorized into *logistical partners*, *formal lawmakers* and *subsidy agencies*. Logistical partners strive for a water side performance that is robust, reliable, continuous and adaptive to future growth in container transshipment. In the *Port Vision 2030*, it is predicted that the container throughput through the Rotterdam harbour almost doubles to 265 million tonnes when compared to 2010 and that the percentage of these containers being transshipped by QCs rises from 25% to 42% (Port of Rotterdam, 2011). Therefore, future electric AGV deployment shall be flexible in terms of increasing workload; for this study, it is thus of importance to test the battery-electric AGV fleet on its operational robustness for the long term. Formal lawmakers have as main objective a fully sustainable, zero-emission, zero-noise port where AGVs shall not emit Green House Gases (GHG). The way in which this should be achieved is mostly left to industrial partners. Governmental subsidy agencies strive, likewise the formal lawmaker, for a sustainable port, though, they differ in available resources: subsidy agencies are facilitating, while formal lawmakers are restrictive. According to the Energie-investeringsaftrek (EIA), which stimulates sustainable energy use, ECT could on average save 13,5% of its original investments in zero-emission vehicles, given 2018's budget of 147 million euros (RVO, 2018a). Additional subsidies can be attained during the development or pilot phase: according to the WBSO regulation, Research & Development labour and prototype costs are both partially covered by this subsidy (RVO, 2018b); the actual amount depends on the eventual costs made.

For this study, the I&E Department is the problem owner. Synthesizing the stakeholder analysis conducted above, Table 4.1 is created which classifies the stakeholders on (Enserink et al., 2010):

- *the degree of dedication*, reflecting the effort each stakeholder takes to accomplish the main objective, an operational and financial successful implementation of battery-electric AGVs at the Delta Terminal.

- *similar or conflicting stakes*, e.g. FD may endorse a cheaper solution while I&E opts for an innovative water side port.

- *critical versus non-critical actors*, where critical actors' stakes must not be ignored due to the dependency on their resources.

Table 4.1: Overview of stakeholders involved in the process towards fully electric AGVs

	Dedicated		**Non-dedicated**	
	Critical	**Non-critical**	**Critical**	**Non-critical**
Similar stake	I&E TOD Formal lawmaker	Subsidy agencies	LD FD	Logistical partners
Opposite stake				

From the table, it can be seen that all actors involved have similar interests; they all opt for a successful transition towards zero-emission, zero-noise AGVs. However, the critical LD and FD departments are not *triggered* yet to cooperate in the implementation phase due to a lack of knowledge on the effects of battery-electric AGVs on AGV downtimes and capital and operational expenditures respectively. Therefore, it is important to design a charging system that is operationally and financially viable.

4.3.2. Design requirements and constraints

In this section, the design requirements and constraints with which the AGV charging process should comply are discussed.

Design requirements and criteria

From the problem definition and research question of this study, the only two aspects considered are *operations* and *costs*. When looking at section 4.3.1 and the constructed objective tree in Appendix C, the AGV maintenance environment and required space of charging infrastructure are also important from the TOD and I&E departments respectively. As AGV maintenance is not the focus of this study, this will only be incorporated in the determination of the total costs of ownership in Chapter 7. Regarding space, this is merely a constraint than an actual requirement as brownfield terminals, of which ECT Delta Terminal is an example, do not offer flexibility in their current terminal layout, as obtained from the problem definition in Chapter 1 and when looking at Figure D.2 in Appendix D. In this figure of the DDN layout, where the AGV operational area is highlighted in green, the tanking area in yellow and the AGV forbidden area in red, it can be seen that there is no space left unutilized. Thereby, charging infrastructure to be built could either be installed at the expense of other terminal activities or fit within the current layout. From brownfield operator's perspective, the first option is highly undesirable, thereby, space restrictions will be incorporated as a constraint.
The main requirements on which AGV charging processes are assessed are:

1. Incorporating the AGV charging process into the operational process should lead to equal operational performance compared to the current diesel AGV fleet

2. Implementing a battery-electric AGV fleet and its charging process should lead to equal or lower total costs of ownership compared to the current diesel AGV fleet

From the objective tree in Appendix C, the requirements can be operationalized into concrete criteria.

Operational criteria

Criterion 1: Vessel turnaround times in hours/vessel
Criterion 2: QC-AGV interaction in % of QC moves waiting for AGVs %
Criterion 3: QC productivity in moves/hour/QC

Cost criteria

Criterion 1: Capital expenditures of infrastructure and AGVs in €
Criterion 2: Maintenance expenditures of infrastructure and AGVs over a predefined time horizon in €
Criterion 3: Fueling expenditures of AGVs over a predefined time horizon in €
Criterion 4: Terminal downtime expenditures over a predefined time horizon in €

These operational criteria are used for assessment in Chapter 6; cost criteria are used for the total costs of ownership analysis in Chapter 7.

Design constraints

Whereas designs should comply with requirements as much possible, constraints on the other hand reflect boundaries which may not be violated. From interviews held with LD (see Appendix J for the reference), the most important design constraint is that:

- the AGV charging process shall never hinder QC operations,

since QC productivity is leading in the determination of terminal performance. By interviewing the I&E department (see Appendix J for the reference), the most important and relevant design constraints are:

- the charging technique used shall not cause damage to other terminal equipment and communication systems
- the charging infrastructure shall fit within the current terminal layout
- the charging technique used shall be available on the market

Although the first constraint is obvious, the second constraint follows from the fact that ECT Delta Terminal is a brownfield terminal which does not offer free space or layout adjustment for AGV charging. The third constraint is added since ECT is expecting its next AGV replacement program within 5 years; evaluating 'rocket science' technologies is thereby risky as these products may never become available on the market.
Having identified the main design requirements and constraints, the next step is to functionally decompose the system under study.

4.3.3. Determining system functions

Before elaborating upon system functions, the actual system under study should be adequately mapped. For generating designs the system under consideration covers *all actions that are related to charging AGVs, from the moment an AGV receives a notification from the TOS that it assigned for charging until the AGV has finished charging and starts participating in the container transport process.* Several methods exist which are useful for obtaining and visualizing system functions. Sage and Armstrong (2000) propose the use of Functional Flow Block Diagrams for functional decomposition. Another widely used technique is Integrated Definition for Function Modeling, also known as IDEF0, which separates processes with input, output, required resources and control procedures. For the functional decomposition of the AGV charging process, looked is at the current AGV tanking process depicted in Figure 2.7. From this figure, it is observed that the most important decisions to make within the tanking process are **when** and **where** to tank. For AGV charging, an additional function is added: **how** to charge, as several charging techniques exist (e.g. battery swap, plug-in etcetera). Consequently, these three questions form the core of the designs to be generated.

4.4. Generation of designs

Having defined the main design requirements, criteria, constraints and system functions, the next step is to come up with potential solutions for each system function which comply with the defined constraints and satisfy the requirements as much as possible. By combining solutions across the system functions, charging designs can be generated with the use of a morphological chart. A morphological chart visualizes main system functions column wise and means with which these functions can be deployed row wise (Tayal, 2013). The created morphological chart is depicted in Table 4.2. In the next sections, this morphological chart is explained in more detail.

Table 4.2: Morphological chart with vertically the main system functions and horizontally the means with which these system functions can be achieved

Function / Means	**1**	**2**	**3**	**4**	**5**
When to charge?	Battery level <20%	Whenever opportunity arises			
Where to charge?	ASC TP	QC lane	Edge of AGV area	While driving	
How to charge?	Plug-in	Battery swap	Pantograph	Inductive	Rail

4.4.1. System function 1: when to charge

For the decision when to charge the battery, two possibilities exist: charge when a certain threshold value has been reached or charge whenever the opportunity arises. The first concept has already been described by McHaney (1995) as *automatic charging*, in which AGVs go charging when their battery level has dropped below 20%. The value 20 has been chosen as Lithium-Ion batteries, the battery type chosen for this study, are sensitive to deep discharges below 20%. Currently, this threshold-based refueling concept is already being applied to the diesel AGVs which only go tanking below 200 liters fuel. The second alternative, whenever the opportunity arises, also stems from McHaney (1995), however, for this study the setting is different, i.e. a deep sea container terminal. As was concluded from section 2.4 and Figure 4.2 that two third to three quarter of the total AGV time consists of waiting and idling, it is expected that opportunity charging is an effective way for dealing with AGV battery constraints.

4.4.2. System function 2: where to charge

The second system function mainly covers the distance AGVs must travel to reach the nearest available charging location. For the water side transshipment area of the DDN, four solutions exist:

1. Put charging spots at the ASC TPs in order to allow for charging while waiting for container (un)loading or while idling. Also, as the ASCs are spread over the entire x-direction of container terminals, by smartly dividing charging spots over the available ASCs the covered distance by AGVs can be further minimized.
2. Charging in the QC lane, where AGVs are queuing when waiting for their containers to be (un)loaded by the QC. Section 2.4 already showed that these waiting times take up a significant share in the entire AGV transport cycle. Thereby, charging in this area seems to be a suitable alternative.
3. Charging spots outside or at the edge of the operational area. Next to replacing the current diesel stations by charging stations, additional charging spots can be built at the edge of the AGV area. Though, the average distance covered will increase when compared to charging within the operational zone, which implies a deterioriation in AGV transport performance, especially at larger container terminals.
4. Charging while driving, which incorporates the area in between the ASCs and QCs. As AGVs are allowed to drive rectangularly in all directions, corresponding charging infrastructure must also allow so. Whereas the previous three alternatives have been obtained from analyzing AGV data in Chapter 2, this alternative has been obtained from the literature review conducted in the previous chapter.

4.4.3. System function 3: how to charge

Actual charging of AGVs can be achieved by the charging techniques mentioned in section 3.3.1. These charging techniques have consequently been used as input into the morphological chart.

4.5. Evaluation of alternatives based on constraints

For each system function of the morphological chart, it is checked whether the means came up with do not violate the predefined constraints. These constraints are ranked on order of importance:

1. the AGV charging process shall never hinder QC operations
2. the charging technique used shall not cause damage to other terminal equipment and communication systems
3. the charging infrastructure shall fit within the current terminal layout

4. the charging technique used shall be available on the market

Looking at the morphological chart, four alternatives violate one of the listed constraints and are thus dismissed from further selection.

Charging at QC

From the system function *where to charge*, charging at the QC has been dismissed as it violates the first ranked constraint, QC hinder, during construction and maintenance of the corresponding charging infrastructure. Practice at the Delta Terminal and at other container terminals is that equipment in the vicinity of maintenance activities is shutdown in case of maintenance; shutting down the QC is highly undesirable and therefore this alternative has been dismissed.

Battery swapping

Battery swapping as charging technique has been dismissed as it violates the third constraint, space restrictions. From the morphological chart, three locations for battery swap stations remain: at the edge of the AGV area, at the ASCs and on the AGV grid. As there is obviously no space on the AGV grid for swap stations, battery swapping at the ASCs and at the edge of the AGV area is not possible either as the average swap station's size is 25x25 meters[1]. Since there is neither space at the ASC TPs for these swap stations (see Figure 4.3) - the size of an ASC TP is 15x5 meters - nor at the edge of the AGV area (see Figure D.2, current size of the tanking area is 15x10 meters), this alternative has been dismissed from further selection. The other charging techniques do fit within the current terminal layout, as plug-in, pantograph and rail chargers could be placed either on an ASC TP (see Figure 4.4) or at the lane in between two ASCs (see Figure 4.3), which is 8 meters wide while the current chargers available on the market are 10 footers, i.e. 2.5 meters wide (see Appendix E). At the edge of the operational area, e.g. at the current diesel tanking spots, these chargers could also be placed. Inductive chargers do not consume any physical space as these are placed under the AGV pavement (Lukic and Pantic, 2013).

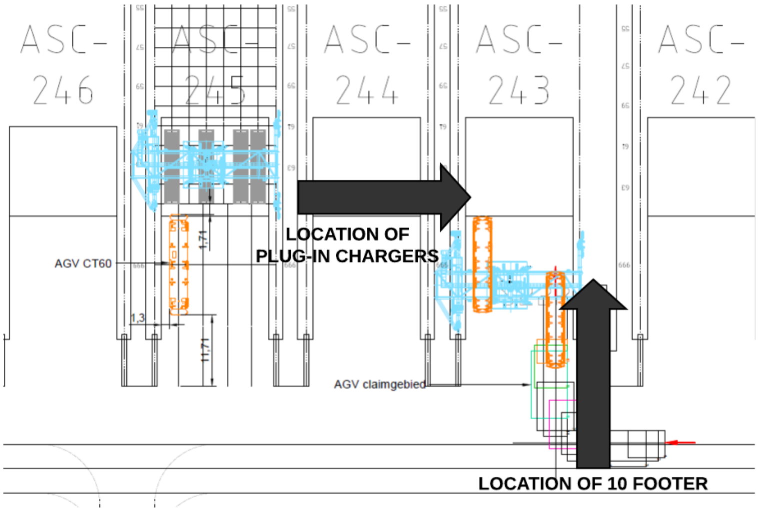


Figure 4.3: Frontal charging at the ASC with corresponding dimensions in meters

Inductive charging

Due to magnetic emissions during inductive charging, this alternative has been dismissed as it violates the second constraint, no damage to equipment and communication systems. In consultation with ECT experts, this alternative is not regarded a viable option as the magnetic emission will cause damage to the AGV-TOS communication system.

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[1] Retrieved from Google Maps by measuring the space of the battery swap station installed at the port of Hamburg (CTA)

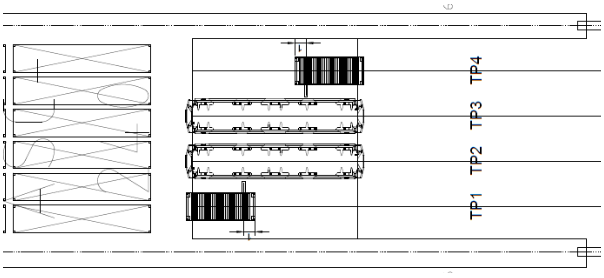


Figure 4.4: Sideways charging at the ASC sacrificing the outer TPs

Charging while driving

Finally, charging while driving has been dismissed as in-motion charging on the AGV grid is technically only feasible in combination with inductive charging. Recalling from Table 3.4, the three charging techniques which are applicable during driving are pantograph, rail and inductive charging. Rail and pantograph charging are not suitable as AGVs drive in a grid structure, thus not in one direction. As a consequence, AGVs are allowed to cross each other, for which rail or pantograph infrastructure installed at the bottom will cause conflicts in AGV routes. Although inductive charging does not physically occupy space at the surface of the AGV grid and is thereby suitable, the resulting magnetic emission will damage the communication system. Therefore, charging while driving has been dismissed.

4.6. Selection of remaining alternatives

By dismissing the four alternatives discussed above, in total 2x2x3 = 12 complete design alternatives of the AGV charging process remain left for selection based on the defined requirements. These requirements are:

- Incorporating the AGV charging process into the operational process should lead to equal operational performance compared to the current diesel AGV fleet
- Implementing a battery-electric AGV fleet and its charging process should lead to equal or lower total costs of ownership compared to the current diesel AGV fleet

The adjusted morphological chart without the dismissed alternatives is depicted in Table 4.3. In the next sections, based on these requirements a selection of the most promising design alternative is made which will be used for further evaluation on its operational and financial feasibility in the next chapters.

Table 4.3: Adjusted morphological chart after constraints evaluation

Function / Means	**1**	**2**	**3**
When to charge?	Battery level <20%	Whenever opportunity arises	
Where to charge?	ASC TP	Edge of AGV area	
How to charge?	Plug-in	Pantograph	Rail

System function 1: when to charge

For the choice when to charge, looking at both operations and costs, charging below a certain threshold value or whenever the opportunity arises only seem to differ in their operational performance. McHaney (1995) listed two operational criteria to choose between charging below a threshold value and opportunity charging:

1. Predictability of AGV routes
2. Share of idle and waiting times in total AGV time

Whenever AGV routes are non-predictable and there is little opportunity for charging, charging below a threshold value is recommended to use from an operational perspective. When the opposite is the case, opportunity charging should be used. As most of the time AGVs are waiting or idling while only 23% of the total time AGVs are actually transporting containers, in combination with the fact that all AGV routes are centrally controlled by a TOS and thus fully predictable, opportunity charging appears to be more effective than charging below 20% battery level. Therefore, charging whenever the opportunity arises outperforms charging below 20% only.

System function 2: where to charge

Considering the location of AGV charging, two alternatives are left: at the ASC TPs or at the edge of the AGV area. Regarding costs, these alternatives mostly do not differ; construction costs may be different due to site specific civil and electrotechnical characteristics, however, this is far out of scope for this study. Regarding operational performance, these alternatives *do* differ on one important criterion: the average distance AGVs have to travel to a charging spot. When looking at the layout of the DDN and container terminals at water side in general in Figure D.2, ASCs are located along the AGV grid, thus the average driving distance is minimized when charging at the ASCs. From section 1.1.2, it was recalled that the average AGV driving distance between ASCs and QCs is 300-400 meters. Locating the charging spots at the ASCs thus results in an average traveling distance of 150-200 meters. Charging at the edge of the AGV area causes substantially higher driving distances, which results in higher AGV charging times, and thus downtimes. Taking the quay length of the DDN into account - 1,000 meters - the average AGV traveling distance to the edge of the area is on average 500 meters. Moreover, since AGVs are frequently waiting at the ASC TPs, it sounds not logical to drive in the mean time to the edge of the AGV area (e.g. to the current diesel tanking spots) for charging. Instead, charging at the ASC TP appears to make more sense and is therefore chosen for further evaluation.

Table 4.4: Operational and cost evaluation of the remaining charging locations

		ASC TP	Edge of AGV area
Operational criteria	Average distance AGV - charging spot [meters]	150-200	500
Cost criteria	no criteria found	-	-

System function 3: how to charge

For the choice of the charging technique, Table 3.4 is of very good use as this table provides a synthesis of literature on charging techniques and strategies. Regarding operations and costs, charging techniques mostly differ on the criteria depicted in Table 4.5. For the operational performance, the speed of charging (charging power) and the charging efficiency, i.e. what percentage of charging energy is effectively being transferred to the AGV battery, are of importance for the determination of the most suitable charging technique. Regarding costs, chargers only need to be installed and maintained. Most of the costs appear at the beginning with the purchase and installment of the charging infrastructure within the existing infrastructure. Maintenance costs appear afterwards in the form of annually recurrent costs. While the other criteria can be deducted quantitatively, the maintenance sensitivity is operationalized on a qualitative scale; synthesizing from Table 3.4, it is concluded that rail charging is most sensitive to maintenance as the rails are both sensitive to wear and adverse weather conditions, while plug-in and pantograph charging are only affected by wear due to moving parts. Therefore, rail charging is chosen to score a minus while the other two charging techniques score more beneficial on this criterion.
From Table 4.5, it is observed that *plug-in* charging financially outperforms the other two techniques, while scoring operationally equal compared to pantograph charging. Therefore, it appears logical to select plug-in charging as main charging technique.

Final AGV charging process design

By filtering the design alternatives shown in the original morphological chart of Table 4.2 on the design constraints and requirements, it is shown that **opportunity plug-in charging at the ASC TPs** is most promising to be implemented as AGV charging process into the operational process at brownfield container terminals. For the remainder of this study, this design alternative will consequently be evaluated on its operational and financial performance by using the criteria listed in section 4.3.2 in order to provide an answer to the main research question "Is it operationally and financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?".

Table 4.5: Operational and cost evaluation of the remaining charging techniques

		Plug-in	**Pantograph**	**Rail**
Operational criteria	Maximum charging power [kW]	600	600	120
	Charging efficiency [%]	97	97	97
Cost criteria	Infrastructure costs [€]	200,000	300,000	1,000,000
	Maintenance sensitivity	+/-	+/-	-

4.7. Conclusion

This chapter aimed at answering the third subquestion,
3. Which design of the charging process can be used for further evaluation based on brownfield terminal operator's requirements and constraints?
by defining this study's problem owner's main design requirements and constraints, decomposing the system under design into its core functions, trawling alternatives for each of the system functions and finally by selecting the most promising complete AGV charging design based on the defined requirements and constraints. Output of the previous chapters has been used as input for the design alternatives and evaluation.
By means of a stakeholder analysis, it was found that ECT's logistical and financial departments are not triggered yet to cooperate in the acquisition of battery-electric AGVs due to the unknown impact on terminal operator's operations and finance. As a result, the main design requirements of this study are:

1. Incorporating the AGV charging process into the operational process should lead to equal operational performance compared to the current diesel AGV fleet
2. Implementing a battery-electric AGV fleet and its charging process should lead to equal or lower total costs of ownership compared to the current diesel AGV fleet

These requirements are operationalized into measurable quantities, i.e. criteria:
Operational criteria
Criterion 1: Vessel turnaround times in hours/vessel
Criterion 2: QC-AGV interaction in % of QC moves waiting for AGVs %
Criterion 3: QC productivity in moves/hour/QC

Financial criteria
Criterion 1: Capital expenditures of infrastructure and AGVs in €
Criterion 2: Maintenance expenditures of infrastructure and AGVs over a predefined time horizon in €
Criterion 3: Fueling expenditures of AGVs over a predefined time horizon in €
Criterion 4: Terminal downtime expenditures over a predefined time horizon in €

Furthermore, the constraints with which AGV charging designs must comply are:

1. the AGV charging process shall never hinder QC operations
2. the charging technique used shall not cause damage to other terminal equipment and communication systems
3. the charging infrastructure shall fit within the current terminal layout
4. the charging technique used shall be available on the market

By dividing the AGV charging process into *when*, *where* and *how* to charge, alternatives have been trawled for each of these system functions into a morphological chart. By combining alternatives over the system functions, a complete AGV charging process design is generated. By evaluating all designs on the predefined requirements and constraints, **opportunity plug-in charging at the ASC TPs** turned out to be the most promising AGV charging process design and is therefore selected for further evaluation on its operational and financial feasibility in the next chapters. The main output of this chapter is thereby the functional design of the AGV charging process which is consequently tested on its operations and costs in order to provide an answer to the main research question "Is it operationally and financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?".

5

Simulation model building

This chapter aims at providing the reader the methodology choice, model structure, verification and validation which forms the basis for the operational assessment of the selected design of the AGV charging process from the previous chapter, *opportunity plug-in charging at the ASC TPs*, to the current situation with diesel AGVs in order to answer the fourth subquestion of this study:
4. How does the selected design of the AGV charging process influence the operational performance when compared to diesel AGVs?
Therefore, the model has been built up for diesel AGVs by default, after which the model is adjusted and extended to the selected AGV charging design in section 5.7. More specifically, section 5.1 starts with a description of the choice, purpose and expected output of the methodology used, after which section 5.2 elaborates upon the simulation software selection, terminal elements included in this study's scope and their process descriptions by using the Process Description Language according to the Delft Systems Approach. Sections 5.3 and 5.4 discuss the interactions between the model elements and the models' control architecture respectively, whereafter section 5.5 describes the most important model input and output. Section 5.6 dives into the verification and validation of the developed model *for the diesel AGV version*, as diesel AGVs are used as default. Finally, this chapter ends with the implementation, verification and validation of the incorporated AGV charging process from Chapter 4 into the default diesel AGV model in section 5.7 and with a conclusion of the chapter in section 5.8. Figure 5.1 visualizes this chapter's structure together with the main output and relations between the sections.

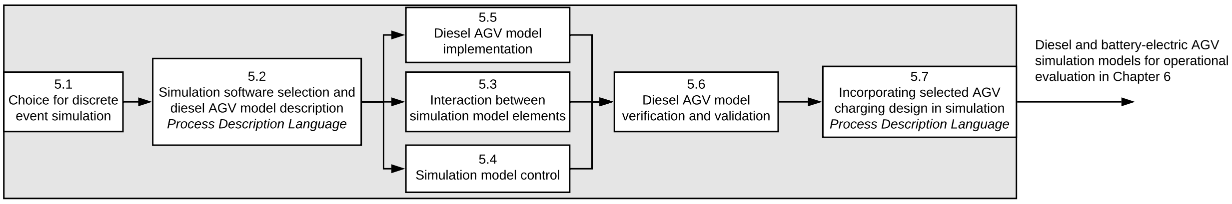


Figure 5.1: Structure, methods and output of Chapter 5

5.1. Choice for discrete event simulation

For this study, simulation is chosen as methodology to evaluate the operational feasibility of charging AGV batteries at container terminals due to the fact that analytically resembling container transport at the operational level is very complex. Moreover, simulation offers the user the ability to quickly run several scenarios, for which analytical derivations would take significantly more time. Regarding the type of simulation, generally three simulation specifications can be distinguished (Schriber et al., 2014):

- *Differential Equation System Specification*, which assumes that the time base is continuous and that system states are a continuous function of time

- *Discrete Time System Specification*, which assumes that the time base is discrete and that system states are modeled as difference equations of time
- *Discrete Event System Specification*, which states that time is continuous while system states change discrete over time, i.e. are constant for variable periods of time

From these specifications, the last one best resembles container operations as time is continuous while equipment, e.g. AGVs and ASCs, is sequentially waiting on the other equipment to perform the next activity, e.g. an AGV waits on a TP until an ASC has loaded a container on top. More practically speaking, the first two specifications are merely used for continuous simulation, where variables are continuously changing over time (e.g. filling a water tank), while the last specification better fits discrete interaction between objects or elements. Therefore, chosen is for discrete event simulation rather than for continuous simulation.

5.1.1. Purpose and expected output of the simulation model

The main purpose of the developed simulation model is to gain insight into the operational feasibility of battery-electric AGVs at brownfield container terminals when compared to the current situation with diesel AGVs. More specifically, by using the operational criteria listed in Chapter 4 and depicted in Figure 2.4, a concrete change in terminal performance can be observed between the two fleets. For this purpose, two simulation models have been developed: a diesel AGV and battery-electric AGV variant. The diesel AGV simulation model is built as default, after which this model is adjusted and extended to the selected design of the AGV charging process from the previous chapter, *opportunity plug-in charging at the ASC TPs*. The expected output of this simulation study are statistical values and graphs which support the assessment of the operational feasibility of this AGV charging design; this output is elaborated upon further in Chapter 6. Now having discussed the choice for discrete event simulation and purpose and output of the simulation study, the remainder of this chapter is dedicated to the techniques used to build the model.

5.2. Simulation software selection and model description

In order to realistically and effectively evaluate the operational feasibility of electric charging at brownfield container terminals, the current situation with diesel AGVs has been modeled and implemented in simulation software in order to compare its logistical performance with a full electric AGV fleet. Borland Delphi with TOMAS extension has been used due to its process-oriented, discrete event approach, which is especially useful for modeling simultaneous and interacting (and competing) terminal operations (TOMAS is mostly being used for the simulation of AGV systems). TOMAS stands for *Tool for Object-oriented Modeling And Simulation* and, as the name reveals, is next to process-oriented also object-oriented (Veeke and Ottjes, 2000). These two orientations become observable when programming in TOMAS: based on the element classes defined by the user, processes are specified for those elements that are assigned a process. More practically speaking, TOMAS enables the user to integrate terminal equipment processes with their corresponding terminal equipment (e.g. AGV process of transporting containers only defined for the AGVs in the simulation, not for QCs/ASCs). Also, TOMAS offers the user statistical results on the main system elements, which is especially useful with regard to the evaluation of the defined operational criteria in Chapter 4.

To provide the reader a proper understanding of the developed terminal model, the Process Description Language (PDL) as proposed by the Delft Systems Approach has been applied, with which system elements and their (interacting) processes are presented in plain language rather than using an overload of simulation specific commands. Using a PDL helps the simulation builder in identifying interaction points between system elements, while assisting the reader in tracking the decision making process of each system element (e.g. ASC, QC, AGV process). The Delft Systems Approach and TOMAS make use of *queues* for interaction between model elements; an element's instance is able to enter a queue of either another element's instance or a global queue - that is a queue which is not element specific (not an attribute of an element class). Consequently, an AGV is e.g. able to enter a QC specific *AGVsWaiting* queue once the AGV has arrived at the corresponding QC TP. Before elaborating upon these interactions, the main system elements to be used are described.

5.2.1. Building blocks of the simulation model

Considering the current operations of container terminals at water side with diesel AGVs and taking into account the physical and operational scope of sections 2.1 and 2.2, generally four elements can be distinguished:

1. Containers

2. QCs
3. AGVs
4. ASCs

Of the above elements, only the latter three are active, i.e. have a process defined; these processes are further specified in the following sections. To make the simulation complete, four extra elements are created:

1. *Ships*, which are used to resemble the container arrival pattern at container terminals as much as possible. Thereby, the ships in the simulation model are merely relevant for the containers they are carrying, which are also model elements. Also, including ships instead of spawning a batch of containers only provides the opportunity to include a ship's berthing time during which battery-electric AGVs could go charging. Although ships are not within the scope of this research, for these two reasons, resembling the container arrival pattern and providing opportunities for charging, ships are included into the simulation model.

2. *Ship Generator*, which generates ships according to a predefined inter arrival time function, which could either be stochastic or deterministic. In this research, a strict distinction is made between MAIN and BARGE vessels; whereas MAINS are characterized by (very) large container discharge and load sizes, BARGES reflect the opposite. Consequently, a MAIN and BARGE generator have been created separately, each having their own inter arrival time distributions and load and discharge sizes. Obviously, BARGES have a shorter inter arrival and mooring time than MAINS.

3. *QC Groups*, which form a collection of QCs handling the same ship. When looking at Figure D.3, the green shapes resemble QCs. It can be seen that 4-5 QCs handle a single MAIN, while a BARGE needs 1-2 QCs. Main advantage of defining QC groups lies in the assignment of QCs to ships: as the number of QCs is fixed, no interchange between ships takes place, thereby reducing the modeling complexity. Moreover, a QC group allows to control the overall discharge and loading process of a ship, which is generally less complex than decentralized control by individual QCs (Ramadge and Wonham, 1989).

4. *Tanking stations*, which facilitate AGVs' diesel refueling. Note that sections 5.2.2, 5.3, 5.5 and 5.6 consider the current situation with diesel AGVs only; electric charging logic is explained later in this chapter.

As TOMAS is next to process-oriented also object-oriented, attributes are assigned to all the above specified element classes, which can either be instantiations of other element classes, TOMAS queues, TOMAS distributions or constants/variables. Table 5.1 shows all attributes that are used in the simulation model; e.g. the *Ship* class owns an attribute *MyQCGroup*, which is an instance of *QCGroup* class (meaning that all ships that are spawned have a specific QC Group to moor at), a TOMAS queue *LoadToBeHandled* and a constant *Berthing Time*. Consequently, all ships that are created during a simulation run own these attributes.
Next to class-specific attributes, global variables are defined which are defined for all simulation elements rather than for a specific element's process. The most important global variables are depicted in Table 5.2, which will be explained in more detail in section 5.2.2.

For the simulation model, the equipment configuration and throughput characteristics of the DDN are used as the DDN is the physical scope of this research. However, since the DDN is mostly similar to other deep sea container terminals around the world, the simulation model may be generalized as well and will thus not be case specific. Nevertheless, chosen is also for the DDN because of the reduction in dimensionality: lower throughputs imply a smaller number of AGVs needed for transport, therefore, deploying electric AGVs will most likely start at the DDN rather than at the larger side of the Delta Terminal, the DDE.
The dimensions of the DDN, as calculated using Figure D.3 with corresponding x and y positions for the QCs, ASCs and tanking stations, are used as input into the simulation model; AGVs are initialized at the center of the terminal.
Finally, it is noted that all information regarding container destinations, ship arrival times and other container handling related data is retrieved via the *container* class. This thus implies that all containers have attributes such as *source QC*, *destination QC*, *source ASC*, *destination ASC* and corresponding x and y positions.

Table 5.1: Element classes and their attributes, sorted on instantiations of other element classes, TOMAS queues, TOMAS Distributions and constants/variables

Attributes/Element classes	**Ship**	**Container**	**Ship Generator**	**QC Group**	**QC**	**AGV**	**ASC**	**Tanking Station**
Element instance	MyQCGroup	MyAGV, MyDestinationQC, MySourceQC, MyDestinationASC, MySourceASC, MyShip, MyQCGroup	-	MyShip	MyAGV, MyQCGroup, MyContainer	MyContainer	MyAGV, MyContainer	MyTankingAGV
Tomas Queue	LoadToBeHandled	-	-	MyQCs	MyAGVsWaiting	-	MyAGVsWaiting, StackContainersWaiting	WaitingForTanking
Tomas Distribution	-	-	IntArrivalDist, DischargeDist, LoadingDist	-	MyHandlingTimeDist	-	MyHandlingTimeDist	-
Constants	Mooring Time	MyXposition, MyYposition	-	MyXposition, MyYposition	MyXposition, MyYposition	FuelLoad, MyXposition, MyYposition	MyXposition, MyYposition	MyXposition, MyYposition

Table 5.2: Global variables sorted on TOMAS queues and constants

	Global variable
TOMAS Queue	MAINShipsWaiting, BARGEShipswaiting, AvailableMAINQCGroups, AvailableBARGEQCGroup, AvailableAGVs, QCsWaiting, ASCswaiting,
Constant	AGVSpeed, QCGroupsMAIN, QCGroupsBARGE, QCsMAIN, QCsBARGE, AGVs, ASCs

5.2.2. Simulation model assumptions and element processes

For the definition of element processes, several modeling assumptions have been made:

- Only the water side area of the Delta Terminal is considered in the simulation model, the underlying organization of the stack has not been modeled other than fitting a normal distribution to ASC handling data provided by ECT.

- Load and discharge plans are out of scope for this simulation as this will be too difficult to implement. Therefore, it is assumed that loading a ship starts at the moment the ship has been fully discharged. In consultation with ECT experts from the Logistical Department, this assumption will most likely hold: mixed loading and discharging can be deducted from the number of dual cycles performed by AGVs. As this percentage is currently only 4% for the DDN (see Appendix J for the reference), mixed loading and discharging does not occur very often. Moreover, even to account for the 4% dual cycling moves, in the simulation this has been implemented by defining dual cycling at the ASCs, so AGVs could carry a loading container after a discharge container has been successfully delivered.

- As QCs positioned at the center of a ship will potentially handle more containers than QCs located at a ship's edges due to its V shape, in the simulation model these dynamics have been left out. Instead, a ship is considered a 'box' from which QCs can hoist containers regardless of their position. However, it must be noted that only QCs belonging to the same QC Group have access to this 'box'.

- The physical driving of AGVs has not been modeled; instead, an average speed has been used which is obtained from studying AGV driving data. Two driving distances have been analyzed using MATLAB: trips between ASCs for repositioning and trips between ASC and QC for container transshipment. By cross-analyzing QC and AGV data regarding actual QC x and y positions and AGV time stamps, it was found that for inter-ASC transport there is a linear relation between driving distance and time, which results in an average speed of 3.19 m/s, see Figure 5.2. For ASC-QC transport, no significant correlation has been found because of the repositioning of QCs per ship (see Figure 5.3). Consequently, AGV entrances from the driving grid into the QC lane and vice versa are variable as well, for which there is no logic to predict the actual travel distance covered by AGVs. However, when assuming the entrances as depicted in Figure D.3, being the white spaces in between the red blocks, an overall average AGV ASC-QC speed can be retrieved, further assuming that an AGV will always enter the QC lane with minimal driving distance. This speed is equal to 2.76 m/s, which approaches the reference value given by the Logistical Department of 2.5 m/s. Reason why an overall average speed could be obtained is the amount of data analyzed, in total 8224 data points, which smooths out individual miscalculations. To conclude, the speed values for inter-ASC and ASC-QC transport will be used as input into the simulation model. In relation to the deduction of the average AGV speed, an average fuel consumption is used as well, which is based on the distance covered by AGVs. The fuel consumption of diesel AGVs is set at 1.10 liters per kilometer for empty trips and at 1.80 liters per kilometer for loaded trips; for full-electric AGVs powered by Lithium-Ion batteries, the energy consumption is 4.33 kWh per kilometer for empty trips and 7.09 kWh per kilometer for loaded trips, according to the values calculated in section 3.1.

- The layout as depicted in Figure D.3 has been used as representative layout for the mooring space of ships at the quay wall. As can be seen, in total two MAINS and one BARGE can moor at the same time, and four QCs handle a single MAIN while one/two QCs is/are destined for a BARGE. Consequently, two MAIN QC groups with four QCs each and one BARGE QC Group with two QCs have been created in the simulation model, each with a fixed location for the sake of modeling efficiency (from QC data, it was found that QCs' positioning bandwidth is on average 50-75 meters).

- Instead of distinguishing 20 foot and 40 foot containers, one container size, 40 foot, is chosen to reduce modeling complexity. Though, to account for the significant share of 20 foot containers, 15-20% of the total handling size, the QC handling distribution has been adjusted to account for this share (at the DDN, not all QCs have a 2x20 foot spreader, thereby, most of the twin carry 20 foot containers are handled one after another instead of at the same time). As will be shown in the validation section, this assumption does not violate the validity of the simulation model.

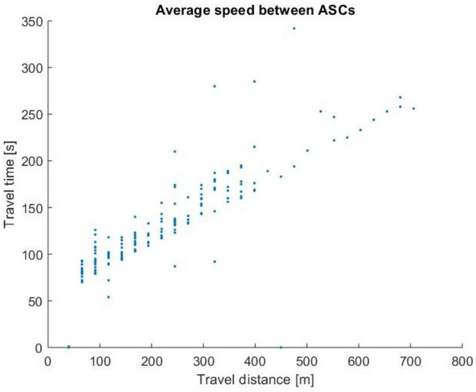


Figure 5.2: Linear relation between driving distance (x-axis) and driving time (y-axis) for AGV inter-ASC transport

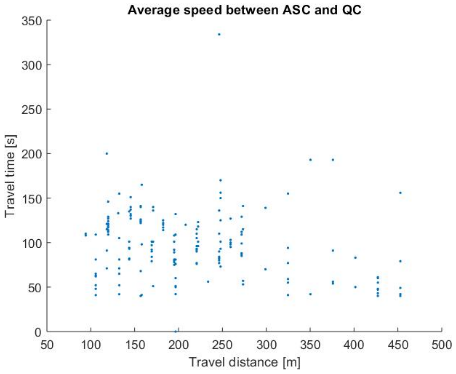
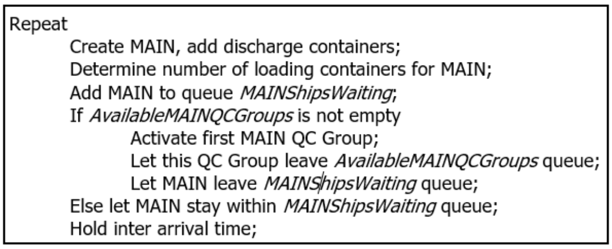


Figure 5.3: No significant relation between driving distance (x-axis) and driving time (y-axis) for AGV ASC-QC transport due to the dynamic positioning of QCs

Procedure 1: Ship Generator

Ships arrive according to an inter arrival time distribution, which is managed by the Ship Generator; this generator is separated in a MAIN and BARGE Generator. Ships with corresponding discharge containers are created. The number of loading containers are determined only, as the actual division over the stacks is being done by the QC Group procedure, which activates once a ship actually moors at the quay wall. After creation, ships are added to a queue of ships waiting. A distinction is made between *MAINShipsWaiting* and *BARGEShipsWaiting* for the sake of easy assignment to QC Groups. As soon as a *corresponding* QC group - that is either a MAIN or BARGE QC group - becomes available, the first ship waiting in the belonging queue is selected for berthing at the quay wall. The reader is referred to Figures 5.4 and 5.5 for the PDL models of the MAIN and BARGE Generator procedures.

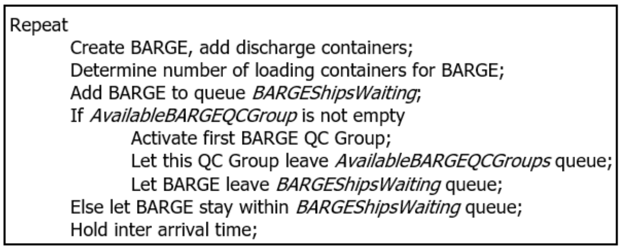


```
Repeat
        Create MAIN, add discharge containers;
        Determine number of loading containers for MAIN;
        Add MAIN to queue MAINShipsWaiting;
        If AvailableMAINQCGroups is not empty
                Activate first MAIN QC Group;
                Let this QC Group leave AvailableMAINQCGroups queue;
                Let MAIN leave MAINShipsWaiting queue;
        Else let MAIN stay within MAINShipsWaiting queue;
        Hold inter arrival time;
```

Figure 5.4: MAIN ship generator procedure in PDL

Procedure 2: QC Group

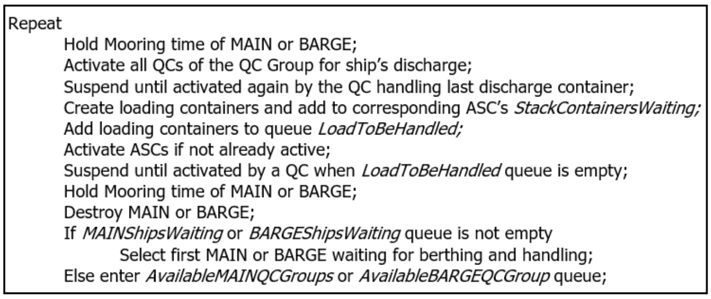
Once either a QC Group becomes available and a corresponding MAIN or BARGE is the first waiting in the *ShipsWaiting* queue, the QC Group activates and lets the ship, carrying discharge containers, berth at the quay wall. Once berthed, a QC Group's belonging QCs are activated which on their turn fully discharge the ship. During this discharge, the QC Group suspends until the QC handling the last discharge container activates the QC Group again. After full discharge, the QC Group reactivates and spawns and distributes the num-



```
Repeat
        Create BARGE, add discharge containers;
        Determine number of loading containers for BARGE;
        Add BARGE to queue BARGEShipsWaiting;
        If AvailableBARGEQCGroup is not empty
                Activate first BARGE QC Group;
                Let this QC Group leave AvailableBARGEQCGroups queue;
                Let BARGE leave BARGEShipsWaiting queue;
        Else let BARGE stay within BARGEShipsWaiting queue;
        Hold inter arrival time;
```

Figure 5.5: BARGE ship generator procedure in PDL

ber of loading containers determined within the corresponding MAINGenerator or BARGEGenerator procedure, according to a uniform distribution, over the available ASCs in their *StackContainersWaiting* queue. Again, the QC Group suspends until the ship has been fully loaded. When completely loaded - which is the case when the corresponding ship's queue *LoadToBeHandled* has become empty - the QC handling the last loading container reactivates the QC Group, after which the QC Group holds again the berthing time of the ship and subsequently destroys the ship. Finally, it is checked whether there are MAINS or BARGES waiting in their belonging *ShipsWaiting* queue. If so, the first MAIN or BARGE is selected for berthing; else, the QC Group becomes idle and enters the queue *AvailableMAINQCGroups* if the QC Group handles MAIN ships, otherwise it enters the queue *AvailableBARGEQCGroup*. The reader is referred to Figure 5.6 for the PDL model of the QCGroup procedure.



```
Repeat
        Hold Mooring time of MAIN or BARGE;
        Activate all QCs of the QC Group for ship's discharge;
        Suspend until activated again by the QC handling last discharge container;
        Create loading containers and add to corresponding ASC's StackContainersWaiting;
        Add loading containers to queue LoadToBeHandled;
        Activate ASCs if not already active;
        Suspend until activated by a QC when LoadToBeHandled queue is empty;
        Hold Mooring time of MAIN or BARGE;
        Destroy MAIN or BARGE;
        If MAINShipsWaiting or BARGEShipsWaiting queue is not empty
                Select first MAIN or BARGE waiting for berthing and handling;
        Else enter AvailableMAINQCGroups or AvailableBARGEQCGroup queue;
```

Figure 5.6: QC Group procedure in PDL

Procedure 3: QC

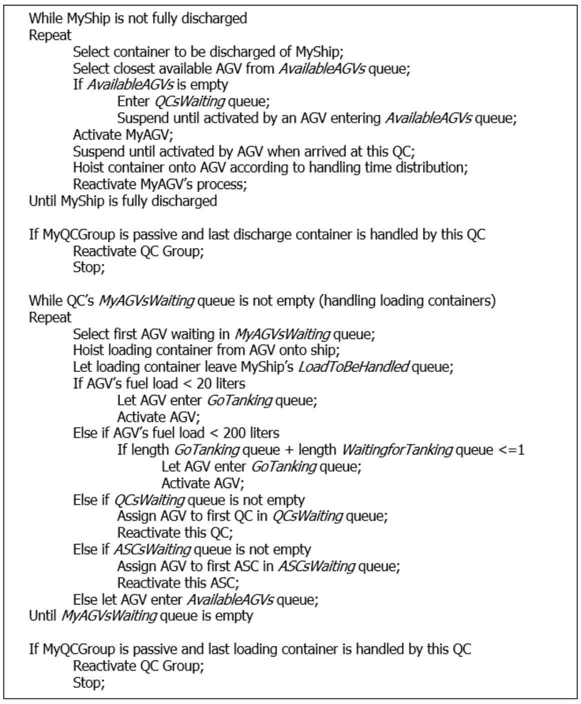
The QC process starts with the discharge of the ship. QCs hoist one container at the time according to a normal distribution, which will be elaborated upon further in section 5.5. However, before hoisting the QC has to make sure an AGV is present in its lane. Therefore, the closest AGV is requested from a global queue *AvailableAGVs*, which forms the basis of the simulation model. With this queue, idle AGVs are requested by either ASCs or QCs. If this queue is empty, the QC enters a *QCsWaiting* queue and suspends until an AGV has become available and reactivates this QC again.

Once an AGV is selected, the QC suspends until the AGV has arrived at the QC TP. Subsequently, the QC hoists a discharge container onto the AGV according to a sample of the QC's handling time distribution, which is further explained in section 5.5. Hereafter, the AGV is reactivated and the QC selects a next container for discharge. If the last container has been discharged from the ship, the QC reactivates its QC Group and stops its own process.

From the QC Group procedure, it was observed that after discharge the loading of the ship follows. In the QC procedure, the actual loading is explained in the last *while* loop; if AGVs with a loading container on top are waiting on a QC's TP, the QC hoists the AGV's container onto the ship. It then checks if the AGV either has to tank or drive to another QC or ASC waiting for an available AGV. For this simulation, it is chosen to let AGVs always drive to a tanking station if their fuel load has dropped below 20 liters. However, AGVs are already able to tank if their fuel load is under 200 liters; whether AGVs actually go tanking below this threshold depends on the amount of other AGVs that are on their way for tanking or are waiting for tanking. Whenever this number is at most 1, the QC assigns this AGV for tanking. Obviously, this assignment of AGVs by QCs is not realistic due to the fact that the TOS is responsible for this job. However, since this decision-making is not time consuming - that means it takes no simulation time to decide whether or not to let an AGV tank - this modeling decision does not influence the simulation outcomes.

If an AGV's fuel load is more than 200 liters, the AGV is either assigned to a QC waiting or ASC waiting; else, the AGV enters the queue *AvailableAGVs* and becomes idle. Finally, if the loading container handled by the QC is the last container to be loaded - which is the case if the queue *LoadToBeHandled* has become empty - the QC reactivates its QC Group again and stops its own process.

From this extensive process explanation, a priority rule can be observed: QCs get priority over ASCs in the assignment of AGVs that have become available. This has been decided upon since QC productivity is leading in the determination of a terminal's performance. Figure 5.7 shows the PDL of the QC procedure with this priority rule in more detail.



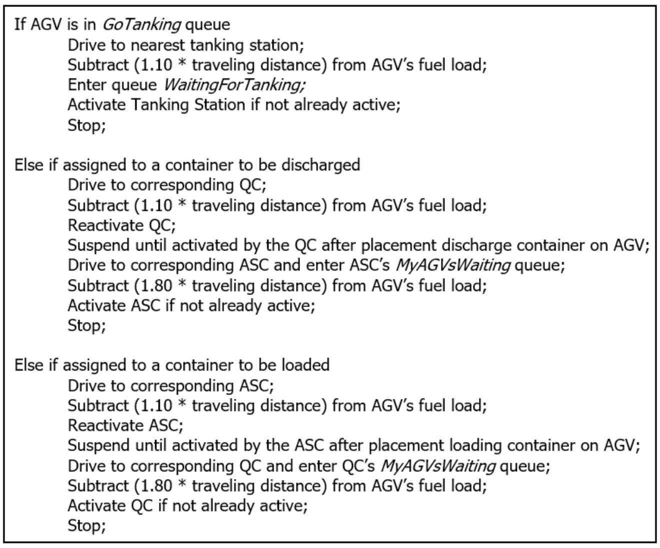
```
While MyShip is not fully discharged
Repeat
    Select container to be discharged of MyShip;
    Select closest available AGV from AvailableAGVs queue;
    If AvailableAGVs is empty
        Enter QCsWaiting queue;
        Suspend until activated by an AGV entering AvailableAGVs queue;
    Activate MyAGV;
    Suspend until activated by AGV when arrived at this QC;
    Hoist container onto AGV according to handling time distribution;
    Reactivate MyAGV's process;
Until MyShip is fully discharged

If MyQCGroup is passive and last discharge container is handled by this QC
    Reactivate QC Group;
    Stop;

While QC's MyAGVsWaiting queue is not empty (handling loading containers)
Repeat
    Select first AGV waiting in MyAGVsWaiting queue;
    Hoist loading container from AGV onto ship;
    Let loading container leave MyShip's LoadToBeHandled queue;
    If AGV's fuel load < 20 liters
        Let AGV enter GoTanking queue;
        Activate AGV;
    Else if AGV's fuel load < 200 liters
        If length GoTanking queue + length WaitingforTanking queue <=1
            Let AGV enter GoTanking queue;
            Activate AGV;
    Else if QCsWaiting queue is not empty
        Assign AGV to first QC in QCsWaiting queue;
        Reactivate this QC;
    Else if ASCsWaiting queue is not empty
        Assign AGV to first ASC in ASCsWaiting queue;
        Reactivate this ASC;
    Else let AGV enter AvailableAGVs queue;
Until MyAGVsWaiting queue is empty

If MyQCGroup is passive and last loading container is handled by this QC
    Reactivate QC Group;
    Stop;
```

Figure 5.7: QC procedure in PDL

Procedure 4: AGV

AGVs drive either to a QC or to an ASC with an average speed of 2.76 m/s; when driving from one ASC to another, the average speed equals 3.19 m/s. When driving to a discharge or loading container after a request, first (1.10 liters * traveling distance) is subtracted from the AGV's fuel load. Subsequently, the corresponding QC or ASC is reactivated after which the AGV suspends until its container is loaded on top (either discharge or loading container). Hereafter, the QC/ASC wakes up the AGV after which the AGV drives to the destination of its container. From its fuel load, (1.80 liters * traveling distance) is subtracted since the AGV is now loaded. Finally, the AGV reactivates either the QC or ASC after arrival at its TP and stops its own process.

Nevertheless, AGVs may also drive to and from a tanking station located at the edge of the terminal (see Figure D.2 for the location of the tanking spots at the DDN). This is only the case if the AGV is in the global queue *GoTanking*, in which it is being assigned by either a QC or ASC after handling of a container. Figure 5.8 presents the AGV procedure in greater detail. Important to address is that AGVs are requested for a transport job and do not actively search for containers themselves: this is being done by the QCs and ASCs.



```
If AGV is in GoTanking queue
    Drive to nearest tanking station;
    Subtract (1.10 * traveling distance) from AGV's fuel load;
    Enter queue WaitingForTanking;
    Activate Tanking Station if not already active;
    Stop;

Else if assigned to a container to be discharged
    Drive to corresponding QC;
    Subtract (1.10 * traveling distance) from AGV's fuel load;
    Reactivate QC;
    Suspend until activated by the QC after placement discharge container on AGV;
    Drive to corresponding ASC and enter ASC's MyAGVsWaiting queue;
    Subtract (1.80 * traveling distance) from AGV's fuel load;
    Activate ASC if not already active;
    Stop;

Else if assigned to a container to be loaded
    Drive to corresponding ASC;
    Subtract (1.10 * traveling distance) from AGV's fuel load;
    Reactivate ASC;
    Suspend until activated by the ASC after placement loading container on AGV;
    Drive to corresponding QC and enter QC's MyAGVsWaiting queue;
    Subtract (1.80 * traveling distance) from AGV's fuel load;
    Activate QC if not already active;
    Stop;
```

Figure 5.8: AGV procedure in PDL

Procedure 5: ASC

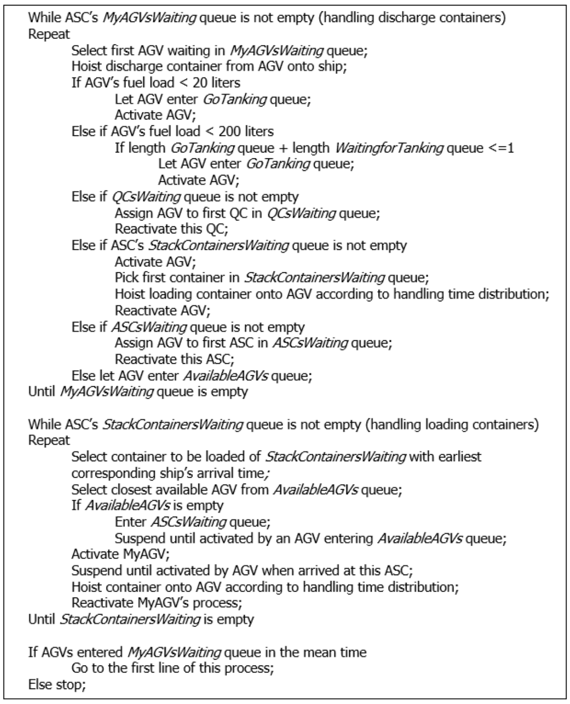
The ASC procedure is very similar to the QC process, only in reverse order. Whereas the QC first discharges containers from its corresponding ship and then checks whether there are AGVs waiting on their TPs (which is suitable since loading of a ship follows after a complete discharge), the ASC first checks whether there are AGVs waiting on its 4 TPs after which the remaining containers waiting in the stack for loading onto a ship are handled by requesting AGVs from the *AvailableAGVs* queue. This reverse order has been modeled for the sake of quick release of scheduled AGVs. Also, an extra condition is built in the assignment of an AGV after handling of its container: before checking whether there are other ASCs waiting for available AGVs (by looking at the length of the *ASCsWaiting* queue), the ASC checks if there are containers waiting in its ASC specific *StackContainersWaiting* queue. In case containers are indeed present in this queue, the ASC performs dual cycling by loading a container of this queue, **belonging to the ship with the earliest arrival time**, onto the handled AGV. In Figure 5.9, the ASC procedure is depicted in PDL form with its corresponding queues and interactions.

Procedure 6: Tanking

The refueling procedure is active while its *WaitingForTanking* queue is not empty. In this case, the refueling procedure selects the first AGV waiting in this queue for tanking, tanks the AGV (by holding for a particular amount of time, see section 5.5) and sets the fuel load of the AGV to its maximum (see section 5.5 for the input parameters). Finally, the refueling procedure checks if there are either QCs or ASCs waiting for available AGVs; if not, the procedure lets the AGV enter the *AvailableAGVs* queue and repeats its process until the *WaitingForTanking* queue is empty, after which its process is stopped.

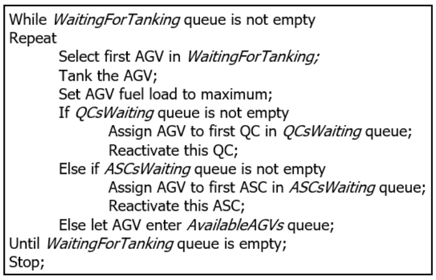
5.3. Interaction between simulation model elements

From the PDL descriptions of the simulation elements, it has become clear that interaction between elements is crucial for the proper working of the simulation model. Several interactions can be observed; as earlier mentioned, in TOMAS interactions between model objects are established by queues. Thereby, several queues have been defined. The first interaction is between the Ship Generator and the QC Group: in case a ship with discharge containers has been generated after a certain inter arrival time, this ship enters a *Shipswaiting* queue which activates the QC Group as soon as this queue length becomes larger than zero. A second interaction is observed between the QC Group and the QCs. As soon as a ship berths, the QCs are activated by the QC Group after which the QC Group *suspends*. When fully discharged, the QCs 'wake up' the QC Group, whereafter the QC Group suspends again. This 'suspend-resume' construction has been frequently used in the simulation model instead of using the 'expensive' command *standby*: when using standby, TOMAS checks after every simulation event whether the condition is violated. Though, using sus-



```
While ASC's MyAGVsWaiting queue is not empty (handling discharge containers)
Repeat
    Select first AGV waiting in MyAGVsWaiting queue;
    Hoist discharge container from AGV onto ship;
    If AGV's fuel load < 20 liters
        Let AGV enter GoTanking queue;
        Activate AGV;
    Else if AGV's fuel load < 200 liters
        If length GoTanking queue + length WaitingforTanking queue <=1
            Let AGV enter GoTanking queue;
            Activate AGV;
    Else if QCsWaiting queue is not empty
        Assign AGV to first QC in QCsWaiting queue;
        Reactivate this QC;
    Else if ASC's StackContainersWaiting queue is not empty
        Activate AGV;
        Pick first container in StackContainersWaiting queue;
        Hoist loading container onto AGV according to handling time distribution;
        Reactivate AGV;
    Else if ASCsWaiting queue is not empty
        Assign AGV to first ASC in ASCsWaiting queue;
        Reactivate this ASC;
    Else let AGV enter AvailableAGVs queue;
Until MyAGVsWaiting queue is empty

While ASC's StackContainersWaiting queue is not empty (handling loading containers)
Repeat
    Select container to be loaded of StackContainersWaiting with earliest
    corresponding ship's arrival time;
    Select closest available AGV from AvailableAGVs queue;
    If AvailableAGVs is empty
        Enter ASCsWaiting queue;
        Suspend until activated by an AGV entering AvailableAGVs queue;
    Activate MyAGV;
    Suspend until activated by AGV when arrived at this ASC;
    Hoist container onto AGV according to handling time distribution;
    Reactivate MyAGV's process;
Until StackContainersWaiting is empty

If AGVs entered MyAGVsWaiting queue in the mean time
    Go to the first line of this process;
Else stop;
```

Figure 5.9: ASC procedure in PDL



```
While WaitingForTanking queue is not empty
Repeat
    Select first AGV in WaitingForTanking;
    Tank the AGV;
    Set AGV fuel load to maximum;
    If QCsWaiting queue is not empty
        Assign AGV to first QC in QCsWaiting queue;
        Reactivate this QC;
    Else if ASCsWaiting queue is not empty
        Assign AGV to first ASC in ASCsWaiting queue;
        Reactivate this ASC;
    Else let AGV enter AvailableAGVs queue;
Until WaitingForTanking queue is empty;
Stop;
```

Figure 5.10: Tanking procedure in PDL

pend aborts the element's process indefinitely until a condition is met (i.e. fully discharge of a ship); this increases modeling efficiency significantly, as was observed during the building of the simulation model. As a consequence, similar constructions are made for interactions between QCs and ASCs waiting and AGVs becoming available and during handling of an AGV at either QC or ASC side. The latter interaction is managed by holding the AGV for a certain amount of time, considering both the changes in x and y coordinates and the average AGV speed.

The most important interactions are perceived between QCs, AGVs and ASCs. AGVs queuing under QCs and at the ASCs have been modeled using an *AGVsWaiting* queue: this queue, with a capacity of 4 at the ASC, handles AGVs one after another according to a normal distribution, which is further specified in section 5.5.

A conceptual model of the simulation logic is depicted in Figure 5.11; a detailed overview of the interactions between QC's, AGV's and ASC's processes with corresponding queues is graphically represented in Figure 5.12. Most important to note is that whenever QCs and ASCs request the same (and only one available) AGV for a container, the QC gets priority over the ASC.

5.4. Simulation model control

Every system requires control in one way or another to choose the actions to be taken by elements present in the system. Whereas ECT applies centralized control, where all actions to be executed by the terminal equipment present on its terminal are determined by a central TOS, for the developed simulation model it is

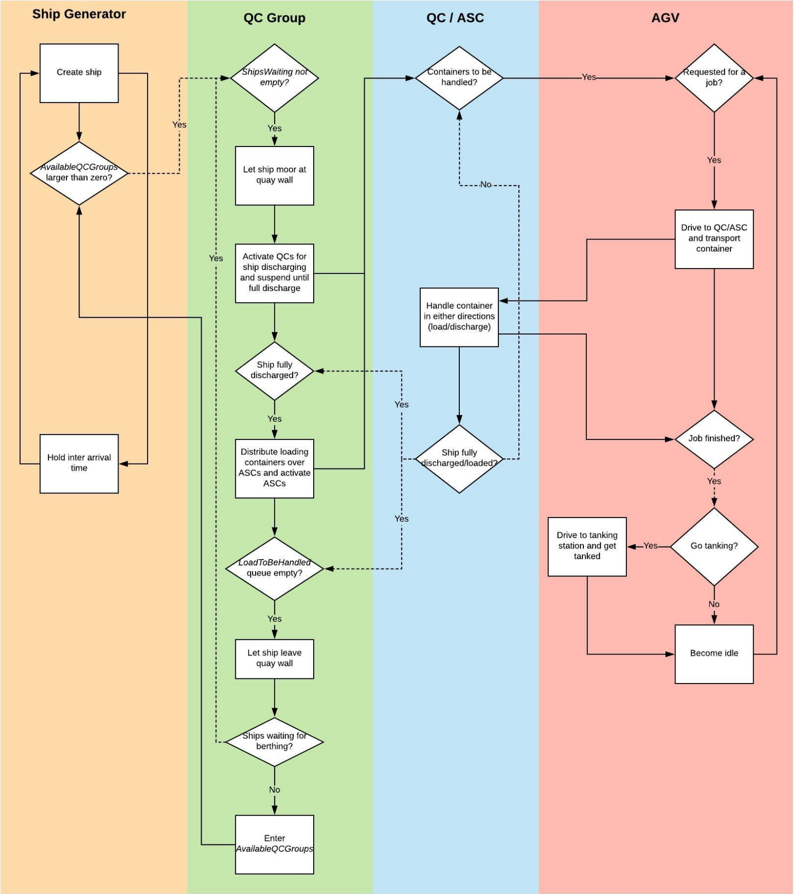


Figure 5.11: Conceptual model of the simulation model

chosen to apply distributed control. Distributed control differs from central control as no supervisory agent is present anymore, i.e. the TOS (Sycara, 1998). Instead, control agents communicate directly with each other rather than via a central controller (Maestre et al., 2009). Main disadvantage, however, of this control type is that the solution might not be the global optimum. Chosen is for distributed control instead of central control by only one process because of the ease in computational efficiency. Assume a decision has to be made regarding the assignment of an AGV to a container waiting in the stack of a particular ASC; central control would yield this central process to be executed from the start until the end (thus evaluating literally every decision that could be made on the terminal for all equipment for all thinkable scenarios). Obviously, this causes extreme computational inefficiency which can be avoided when defining multiple processes which can be separately invoked when a particular decision has to be made.

As mentioned in section 5.2.1, the QCs, ASCs, AGVs, QC Groups, Ship Generators and Tanking/refueling procedure have processes defined. Distributed control results in the simulation control architecture as depicted in Figure 5.13. As can be seen, not all control elements exchange information with each other; instead, the Ship Generator is only allowed to communicate with the QC Group during the berthing of a ship. QC Groups only communicate information with their belonging QCs during discharge and loading of a mooring ship. The QC control agent does not *directly* exchange information with the ASCs and vice versa but via two global queues called *QCsWaiting* and *ASCsWaiting*. Whenever a QC or ASC has handled an AGV, it assigns the AGV to a next job by checking these queues in which QCs and ASCs are waiting for an available AGV (starting with the QCsWaiting as QCs get priority over ASCs). Finally, tanking stations communicate with QCs and ASCs whenever an AGV is assigned for tanking and has not yet arrived at the tanking spot. In case of arrival, the AGV controller exchanges information with the Tanking controller by letting the AGV enter the tanking station's *WaitingForTanking* queue.

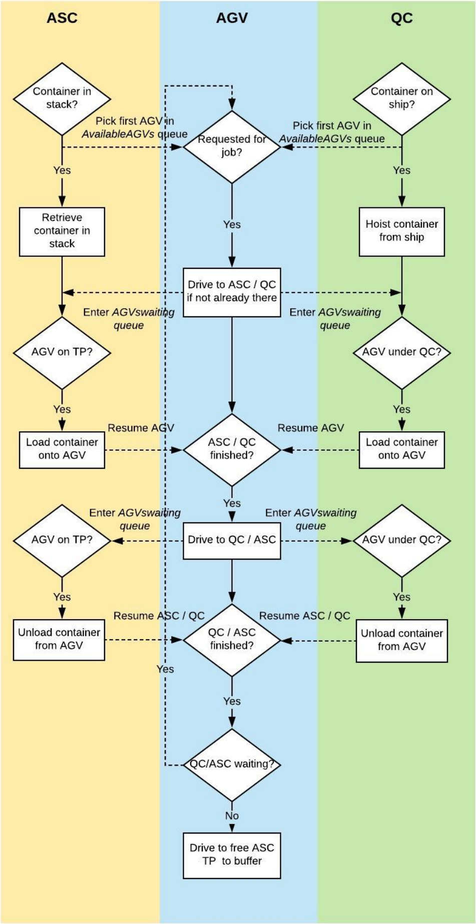


Figure 5.12: Flowchart of the interactions between QCs, AGVs and ASCs

For every control agent, a control cycle can be drawn which incorporates the main control objective, state of the element, actions to be taken in order to reach a particular state and the measurements/outputs of the state transition over time. Figure 5.14 shows the conceptual model of a control cycle. For each of the active simulation elements' controller, control cycles are drawn which are elaborated upon further in Appendix F. For here, it is important to mention two control structures used in the simulation model:

1. While in practice AGVs themselves decide which container to pick up and deliver and whether or not to go tanking, in the simulation model these decisions are made by either the QC or ASC after successful handling of a container from that AGV. This modeling decision is made since it does not affect the simulation outcome: deciding whether an AGV has to tank and which container to pick up next does not consume simulation time and is decided upon immediately. If these decisions were left to the AGVs, complicated interactions would be needed after transport of a container: AGVs should look for themselves which container to pick up by checking all container queues defined (of all ships berthing and all ASCs). As this is now left to the QCs and ASCs, these elements are consequently competing for available AGVs present in the global queue *AvailableAGVs*. This competition, however, is absent in practice, where the TOS schedules AGVs for QCs, ASCs and refueling. To put it briefly, while AGVs have an active role in practice, in the simulation model they are considered to be more passive (although having a process).

2. Checking whether a mooring ship is fully discharged or loaded is in practice the task of the TOS. However, in the simulation model this task is assigned to the element class QC Group, which is created and

specified for this purpose accordingly. Scanning the discharge and loading status of a ship could also be assigned to the individual QCs present along the quay wall, however, to coordinate the activities of QCs belonging to the same ship it is chosen to let a QC Group be responsible for this task. Whenever a QC has handled the last discharge container of a ship, its QC Group is awakened after which the loading of the ship starts. Similarly, after loading the QC Group takes care of the ship's departure. If this was left to the individual QCs (local control), conflicting decisions could be made, e.g. a QC could observe a fully loaded ship and commands the ship to leave the quay wall while another QC is still handling its last loading container. To avoid these situations, a coordinator, the QC Group, has been created.

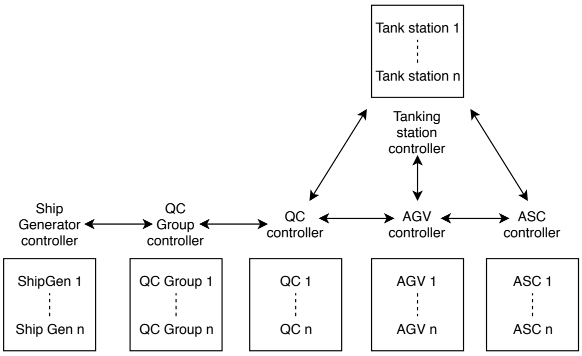


Figure 5.13: Distributed control architecture of the simulation model

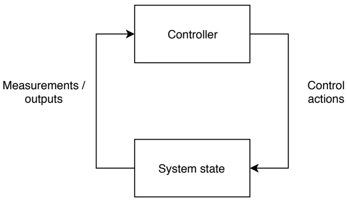


Figure 5.14: Conceptual control cycle model

5.5. Model implementation

Having discussed the main structure of the simulation model, the model input parameters are now described. Regarding the physical terminal layout, the DDN is chosen as study object. The implemented simulation equipment configuration is therefore based on the layout of the DDN in Figure D.3; the configuration of the simulation model is visualized in Figure 5.15. As can be seen, in total 10 QCs and 34 ASCs are included; 4 QCs serve a single mooring deep sea vessel, i.e. MAIN, while 2 QCs serve a BARGE vessel. The QCs are assumed to be fixed and thus do not move which is a simplification of reality. The ASCs are located at stack side and provide the open interfaces with the land side of the terminal. Two tanking spots are located at the edge of the AGV area; in total 65 AGVs drive rectangularly on the AGV grid.

The parameters as presented in Table 5.3 are given a fixed value throughout the simulation, which have been defined in an initialization procedure. Furthermore, operational parameters, such as the handling time of ASCs and QCs and the tanking time, are retrieved from either data provided by ECT or from interviews held with ECT experts from various departments.

5.5.1. Model parameters

Handling time of QC and ASC

For both the QCs and ASCs, handling data is analyzed in order to fit a distribution as input into the simulation model. Chosen is to fit a normal distribution due to (1) the shape of the data output when plotted and (2) to reduce modeling complexity; TOMAS currently only supports uniform, exponential and normal distributions. Other distributions can potentially be constructed, though with (unnecessary) increasing workload. The results of analyzing more than 10,000 data points is shown in Figures F.7 and F.8 in Appendix F. It can immediately be noticed that a large variety exists in QC handling when compared to ASC handling times; this

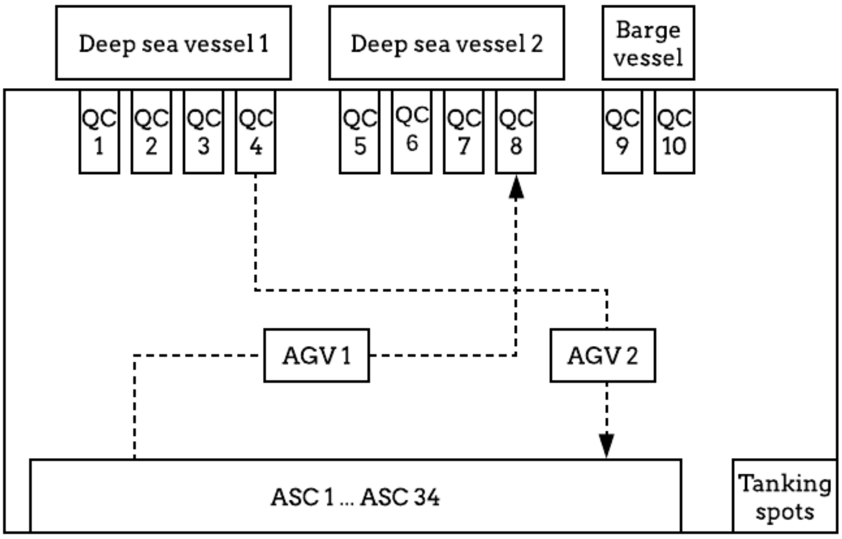


Figure 5.15: Simulation model equipment configuration

is due to the manual loading and unloading process performed by crane operators while ASCs automatically load and unload containers. Yet, the means and standard deviations as obtained from the data are used as input into the simulation model.

Inter arrival times ships

From ship arrival and departure data of two random weeks, inter arrival times for both MAINS and BARGES have been obtained specifically for the DDN. Looked was at the actual arrival and departure times instead of at their estimated counterparts. The results of the analysis are shown in Figures F.9 and F.10. Consequently, the averages of MAINS, 11.73 hours or 700 minutes, and BARGES, 6.35 hours or 380 minutes, are used as mean value for an exponential distribution: this type of distribution is most often used for modeling inter arrival times (Koo et al., 2004).

Container discharge and load sizes ships

For the discharge and load sizes of MAINS and BARGES, a list of loads and discharges for two random weeks has been analyzed. For MAINS, the average discharge size is 551 containers, while a minimum of 200 and a maximum of 1000 containers ensures a sufficient amount of containers being handled. Considering its load size, a MAIN on average loads 628 containers; also here, a minimum of 200 and a maximum of 1200 containers is set.

BARGES on average discharge 34 containers and load 41 containers. A minimum of 15 and a maximum of respectively 130 and 140 containers prevents empty ships from arriving. A normal distribution is used to sample discharge and load sizes for ships during the simulation.

5.5.2. Design KPIs

Main objective of this simulation study is to investigate the operational feasibility of replacing diesel AGVs by battery-electric AGVs in terms of terminal KPIs. Therefore, the KPIs as described in Figure 2.4 and listed in Chapter 4 are used as output of the simulation model - that is the turnaround time time of MAINS and BARGES, QC utilization rate and productivity, average percentage and time of QCs waiting for AGVs and the empty ride fraction of AGVs. When validating the developed model in section 5.6, the KPI outcomes of the simulation model will be compared with actual KPI values, described in section 2.2.3 and illustrated in Appendix A.

Table 5.3: Simulation model parameters

	Parameter	**Value**	**Unit**	**Obtained from**
Layout	Size of terminal	1038 x 119	meters	Delta view
	# QCs per MAIN	4	-	QC data
	# QCs per BARGE	2	-	QC data
	# MAIN QC Groups	2	-	Delta view
	# BARGE QC Groups	1	-	Delta view
	Longitudinal separation QCs	50-75	meters	QC data
	# ASCs	34	-	Delta view
	Longitudinal separation ASCs	25	meters	Delta view
Operational	# AGVs	65	-	ECT experts
	Speed of AGV	2.76	meters/second	AGV and QC data
	Handling time QC	N(104,59), minimum 15	seconds	QC data
	Handling time ASC	N(151,32), minimum 60	seconds	ASC data
	Inter arrival time MAINS	Exp(700)	minutes	Load and discharge data
	Inter arrival time BARGES	Exp(380)	minutes	Load and discharge data
	Discharge size MAINS	N(551,405), minimum 200, maximum 1000	containers	Load and discharge data
	Load size MAINS	N(628,321), minimum 200, maximum 1200	containers	Load and discharge data
	Discharge size BARGES	N(34,70), minimum 15, maximum 130	containers	Load and discharge data
	Load size BARGES	N(41,70), minimum 15, maximum 140	containers	Load and discharge data
Tanking	# Tanking spots	2	-	Practice
	Tanking time	7.5	minutes	ECT experts
	Maximum fuel load per AGV	1200	liters	ECT experts
	Absolute minimum fuel load	20	liters	-

5.5.3. Implementation of diesel AGV tanking in simulation

At the Delta Terminal, AGVs receive notifications when their fuel load drop below 200 and 100 liters respectively. However, it is up to the TOS to decide when to tank the AGVs, which in most cases is done whenever a tanking spot becomes free. For this simulation, an algorithm is implemented in both the QC and ASC controllers which lets AGVs enter a *200litersNotification* queue whenever their diesel tank drops below 200 liters. A second queue, *GoTanking*, is entered by AGVs which are on their way for tanking. As long as the sum of this queue length and the *WaitingForTanking* queue length is at most 1, an AGV that has received a 200 liters notification drives to a tanking spot; otherwise, the AGV continues accomplishing transport jobs until its tank level drops below 20 liters. From this moment, the AGV aborts its operational task (after finishing the last job) and drives to a tanking spot even if there are other AGVs waiting for tanking. This tanking logic is graphically depicted in Figure 5.16. The reader is attended that the actual tanking decisions are made by either a QC or ASC that has just handled a container of the considered AGV, as discussed in section 5.4.
Regarding the fuel consumption of diesel AGVs, the values as calculated in section 3.1.2 and depicted in Table 3.2 are used for empty and loaded diesel AGV trips.

5.6. Diesel AGV model verification and validation

In order to correctly use the developed simulation model for experimental purposes, the inner working of the simulation must be verified. Verification is defined as "ensuring that the computer program of the computerized model and its implementation are correct" and is achieved by asking the question 'Is it the right model?' (Sargent, 2009). Several verification techniques exist, though a selection is made to scope this project:

1. *TOMAS Trace Option*, with which the element processes being executed can be tracked during simulation time. By tracing these processes, the correct working of the model specification can be checked. Appendix F elaborates further upon the TOMAS Trace results, here it suffices to mention that the simulation model works according to the PDL model description.

2. *Seed independence test*, which uses random seeds as input into the distributions specified in the sim-

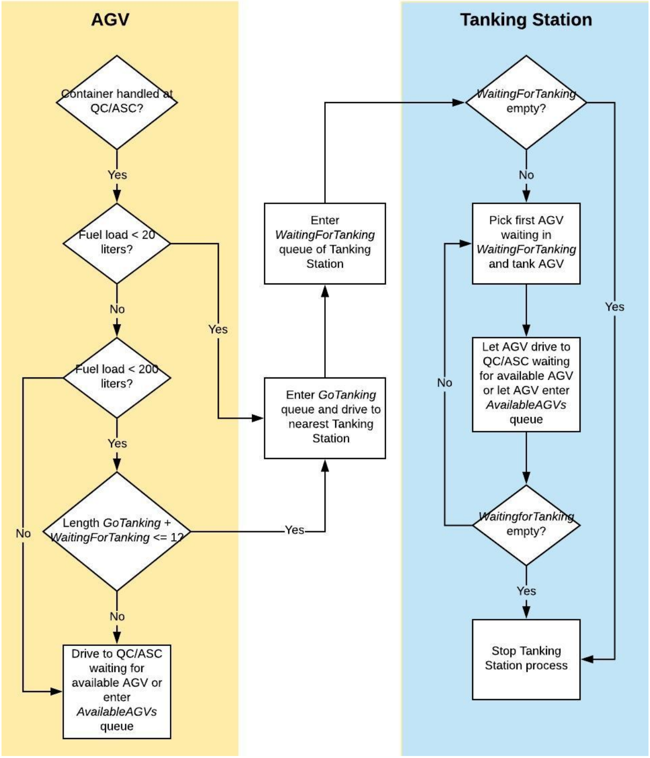


Figure 5.16: Flowchart of the tanking logic implemented in the simulation model

ulation model. Appendix F goes in more detail regarding this verification test, it suffices here to mention that the simulation results show no irregularities regarding the main outcomes. All KPIs fluctuated maximally 5% around the mean value, except from the KPI *percentage of QCs waiting for available AGVs* which fluctuated with 19.7% around the mean value. This large variety with different seeds can be prescribed to the strict way in which this KPI is formulated: even in the situation in which an AGV became available 0.00001 second after a QC was requesting one without success, the QC move counts as *too late* which sounds unfair from a logistical perspective (the corresponding QC had to wait only 0.00001 second for an available AGV). Overall, however, the simulation model is not sensitive to variations in seed input.

3. *Comparison with analytical calculations* using deterministic input. Excluding stochastic behaviour (in the form of distributions) makes it possible to derive gross model outcomes by hand. Appendix F elaborates upon this further by calculating and comparing the average time until full discharge of a ship and the QC productivity. Both calculation outcomes are in accordance with the simulation outcomes, which thus implies that the simulation makes sense from an analytical perspective.

Next to the verification techniques described, some general tests were defined which the simulation model has to pass. Appendix F describes these tests in more detail; for here, it is sufficient to mention that the model passed all checks.

5.6.1. Model validation

Figure 5.17 shows the outcomes of a simulation run for 210,000 time steps, i.e. minutes, or approximately 146 days replicated 3 times. When comparing the simulation outcomes of Figure 5.17 with actual ECT Delta Terminal KPI values described in section 2.2.3, some substantial differences can be observed. First, the turnaround times of MAINS are substantially different from the actual turnaround times. This is most likely due to the fact that the simulation model does not include terminal breaks, which occur three times a day for one hour (after every 8 hours). Thereby, if breaks were included in the simulation, the turnaround time of MAINS would be two hours longer, given that MAIN's turnaround time spans two breaks. As a consequence,

Table 5.4: Comparison of KPI outcomes of the simulation model with ECT DDN Terminal KPIs

	Simulation outcome	Actual value	Difference with actual value	Matching factor simulation - reality
Turnaround time MAIN [hours]	14.3	17.6	3.3	81.3%
Turnaround time BARGE [hours]	3.8	3.3	0.5	86.8%
Containers handled per day [containers/day]	2780	2500-3000	-	within range
QC productivity [moves/hour/QC]	23.0	22	1.0	95.7%
QC utilization rate [%]	76.5	60-70	6.5	91.5%
AGV utilization rate [%]	79.7	70-80	-	within range
Percentage of QCs waiting for AGVs [%]	26.3	16.8	9.5	63.9%
Average waiting time QCs for AGVs [s]	123	145	22	84.8%
Empty AGV trip fraction [%]	43.6	44.2	0.6	98.6%

the relative matching factor with the actual turnaround time would increase to 92.6%.

The percentage of QCs waiting for AGVs is also substantially different from the actual value, most likely due to the way this KPI has been formulated. As ECT works with time stamps, a QC is considered waiting for an AGV once this AGV has not arrived on time at the QC TP - that is within the given time stamp/time frame. In the simulation, however, a QC is considered waiting once it requests an AGV while no AGV is available in the *AvailableAGVs* queue. As a consequence, this method of assigning QCs as 'waiting' is much stricter as it does not allow for slack in the arrival of AGVs, while ECT's method allows to do so (within 1-2 minutes around the preferred arrival time). Since the QCs in the simulation model work on a request basis, QCs do not know on beforehand how many containers they have to handle: no time stamps are included since this is very complex to model (distributions cause stochasticity which is impossible to know on beforehand). Therefore, the percentage of QCs waiting for AGVs turns out to be much higher in the simulation model than in reality. Still, this KPI is important to incorporate in the experimenting phase as battery-electric AGVs are expected to be available a smaller amount of time, which increases the probability of a QC waiting for an available AGV.

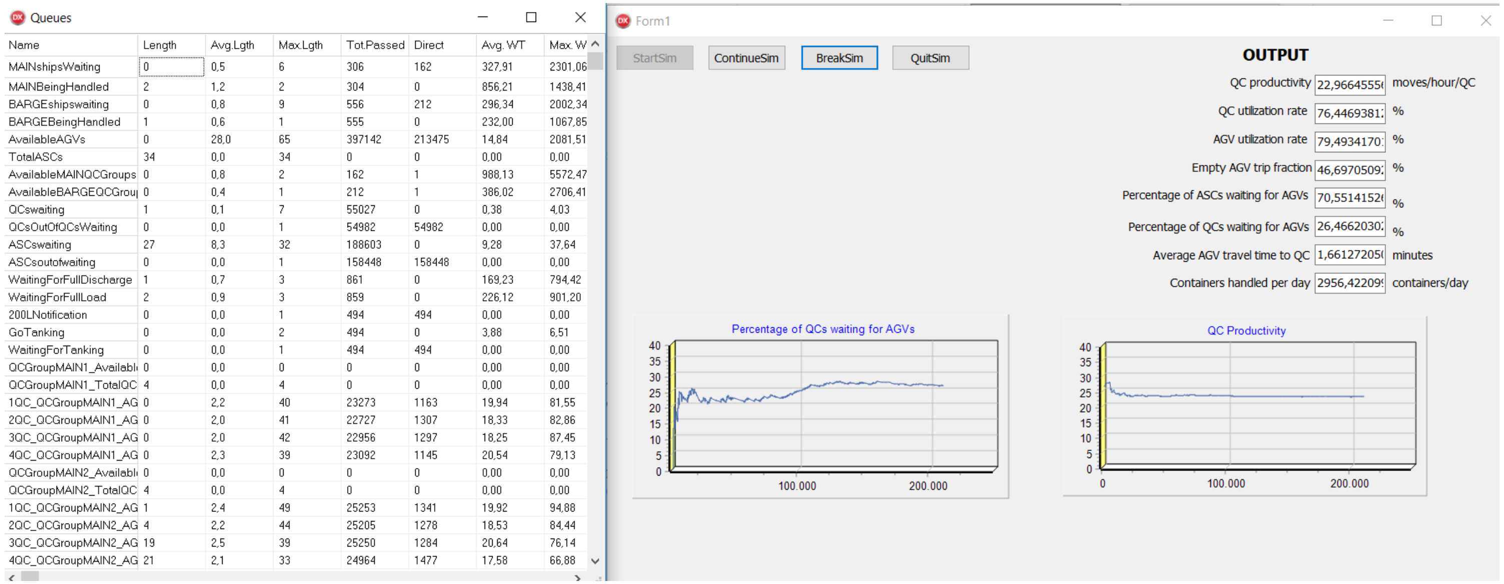
All other KPIs are roughly within the same range as actual ECT DDN values, which thus implies that the simulation model makes sense from a practical perspective (validity). By statistically comparing the means of the simulation and real values, it was investigated whether the KPIs which were obtained by analyzing data - i.e. turnaround times, QC-AGV interaction and empty AGV trip fraction - are also statistically valid. Section F.4 in Appendix F elaborates extensively upon this test; here, it is important to mention that MAIN turnaround times and the percentage of QCs waiting for AGVs are not statistically valid, while BARGE turnaround times and the empty AGV trip fraction *are* statistically validated. However, this does not necessarily mean that the developed model is 'wrong': several possibilities exist which may cause the inaccuracy, of which a few have been mentioned above. As the simulation model's purpose is to compare a base scenario (i.e. diesel AGVs) with an alternative scenario (i.e. battery-electric AGVs), the model's structure and logic, which have been successfully verified, is considered more important than the level of accuracy. For this purpose, the simulation model is considered validated.

The outcomes as presented in Table 5.4 and Figure 5.17 are used as the **diesel** base case for the remainder of the simulation study; the corresponding model input is shown in Table 5.3.

5.7. Incorporating selected AGV charging design in simulation

While the previous sections covered diesel AGVs only, this section comprises the explanation of the simulation logic that is applied for battery-electric AGVs. A separate simulation model has been developed for battery-electric AGVs having much similarities with its diesel counterpart. The procedures of the MAIN and BARGE Generator and QC Groups remain equal; consequently, the QC, AGV, ASC and Tanking procedures have been adjusted.

Before elaborating upon these element procedures, it is mentioned that QCs and ASCs are able to select an available AGV from either the already existing *AvailableAGVs* queue or from a newly created queue, called *ChargingAGVs*. AGVs that are either *driving to a charging spot, waiting for charging* or *actually being charged* are present in this queue. Main reason for adding this queue to the *AvailableAGVs* queue is the fact that the selected design of the AGV charging process of Chapter 4, **opportunity plug-in charging at the ASC TPs**, allows AGVs to charge while still having enough battery capacity to accomplish multiple transport jobs (as this is the main principle of opportunity charging). If a battery-electric AGV e.g. starts to drive to a charging spot with a 45% battery level, this AGV surely should remain available for containers to be handled. In case a container indeed needs to be handled, the AGV is requested by a QC or ASC and, consequently, aborts its own



Name	Length	Avg.Lgth	Max.Lgth	Tot.Passed	Direct	Avg. WT	Max. W
MAINshipsWaiting	0	0,5	6	306	162	327,91	2301,06
MAINBeingHandled	2	1,2	2	304	0	856,21	1438,41
BARGEshipswaiting	0	0,8	9	556	212	296,34	2002,34
BARGEBeingHandled	1	0,6	1	555	0	232,00	1067,85
AvailableAGVs	0	28,0	65	397142	213475	14,84	2081,51
TotalASCs	34	0,0	34	0	0	0,00	0,00
AvailableMAINQCGroups	0	0,8	2	162	1	988,13	5572,47
AvailableBARGEQCGrou	0	0,4	1	212	1	386,02	2706,41
QCswaiting	1	0,1	7	55027	0	0,38	4,03
QCsOutOfQCsWaiting	0	0,0	1	54982	54982	0,00	0,00
ASCswaiting	27	8,3	32	188603	0	9,28	37,64
ASCsoutofwaiting	0	0,0	1	158448	158448	0,00	0,00
WaitingForFullDischarge	1	0,7	3	861	0	169,23	794,42
WaitingForFullLoad	2	0,9	3	859	0	226,12	901,20
200LNotification	0	0,0	1	494	494	0,00	0,00
GoTanking	0	0,0	2	494	0	3,88	6,51
WaitingForTanking	0	0,0	1	494	494	0,00	0,00
QCGroupMAIN1_Availabl	0	0,0	0	0	0	0,00	0,00
QCGroupMAIN1_TotalQC	4	0,0	4	0	0	0,00	0,00
1QC_QCGroupMAIN1_AG	0	2,2	40	23273	1163	19,94	81,55
2QC_QCGroupMAIN1_AG	0	2,0	41	22727	1307	18,33	82,86
3QC_QCGroupMAIN1_AG	0	2,0	42	22956	1297	18,25	87,45
4QC_QCGroupMAIN1_AG	0	2,3	39	23092	1145	20,54	79,13
QCGroupMAIN2_Availabl	0	0,0	0	0	0	0,00	0,00
QCGroupMAIN2_TotalQC	4	0,0	4	0	0	0,00	0,00
1QC_QCGroupMAIN2_AG	1	2,4	49	25253	1341	19,92	94,88
2QC_QCGroupMAIN2_AG	4	2,2	44	25205	1278	18,53	84,44
3QC_QCGroupMAIN2_AG	19	2,5	39	25250	1284	20,64	76,14
4QC_QCGroupMAIN2_AG	21	2,1	33	24964	1477	17,58	66,88

OUTPUT

QC productivity 22,9664555 moves/hour/QC
QC utilization rate 76,4469381 %
AGV utilization rate 79,4934170 %
Empty AGV trip fraction 46,6970509 %
Percentage of ASCs waiting for AGVs 70,5514152 %
Percentage of QCs waiting for AGVs 26,4662030 %
Average AGV travel time to QC 1,66127205 minutes
Containers handled per day 2956,42209 containers/day

Figure 5.17: Simulation results for the diesel AGV model for 146 days, base case

charging procedure by leaving the *ChargingAGVs* queue and starting to drive to the corresponding QC/ASC.

5.7.1. Implemented charging management strategy

When considering the charging strategy, it becomes possible to charge in the loop when an AGV is waiting for a next activity to take place or when becoming idle. As a consequence, batteries do not have to be fully drained onto 20% but can be charged in harmony with the terminal activity. Figures 5.18 and 5.19 show the smart charging strategies that have been developed for battery-electric AGVs that either have handled containers or are requested for a new transport job (thus when becoming idle). Regarding the decision after handling of a container, to avoid deep battery discharges, AGVs always go charging whenever their battery level drops below 20% or when the needed maximum capacity to handle one transport job is not available; for the DDN, this equals traveling empty twice (to a job and from a job to a charging spot) and loaded once 1 kilometer in x-position and 0.1 kilometer in y-position, thus equaling:

$$1.1 * 7.09 + 2.2 * 4.33 = 18\text{kWh} \tag{5.1}$$

Also, if there is an opportunity for an AGV to charge, i.e. when a charger is unscheduled, the AGV will charge its battery (chosen is for 50% to avoid too frequent charge trips as a base case, in the simulation phase this threshold will be varied).

Regarding the release of an AGV by a charger, a charging spot always picks the AGV with the lowest battery level for charging and charges this AGV until 30%. It then checks whether there are QCs or ASCs waiting for AGVs; if so, the AGV is assigned a transport job. Otherwise, the AGV continues charging until 50%, whereafter the charger checks if there are other AGVs waiting for charging with a battery level lower than 50%. If so, the charging AGV leaves the charging spot to make space for the waiting AGV. Main reason for this decision is to evenly distribute the available charging time over all AGVs, while guaranteeing a sufficient capacity after charging. Finally, the AGV is charged until 80%, after which slow charging is applied for the remaining 20%.

To maintain sufficient availability of battery-electric AGVs during peak periods, AGVs that are either driving to a charging spot, waiting for charging or charging while having a battery level higher than 30%, can always be requested by QCs/ASCs. As Figure 5.19 shows, a hard condition is that an AGV's battery level must be 30% or higher in order to minimize the amount of necessary (i.e. < 20% battery level) trips to charging spots by AGVs.

5.7.2. Adjusted PDL models

As the Ship Generator and QC Group procedures have not been adjusted, these procedures are not again discussed. For the adjustments of the other PDL models, Figures 5.18 and 5.19 serve as a guideline. Adjustments made in the PDL models are highlighted in bold.

QC/ASC

In adjusting the PDL models, the QCs and ASCs showed to have much similarities in their transition to battery-electric AGVs because of their comparable task in the diesel AGV simulation model: QCs and ASCs both request AGVs from the *AvailableAGVs* queue for the transport of a container and they both release an AGV after container handling by first checking whether this AGV needs to tank, after which it is checked whether there are other containers that need to be transported. The adjusted PDL models of QCs and ASCs are shown in Figures 5.20 and 5.21 respectively.

Regarding QCs, instead of searching for available AGVs in *AvailableAGVs* only, the QC now also looks at the *ChargingAGVs* queue. In case an AGV is selected from this latter queue, the corresponding energy consumption for driving to the charging spot is subtracted only in case the AGV was still on its way driving to the charging spot; if the AGV already arrived at the charging spot, the AGV procedure takes care of this subtraction. It should also be explained why an extra battery level condition of > 30% chosen: in order to reduce the number of inefficient trips to a charger, a threshold is set to which AGVs' batteries will always be charged. When looking at the handling process of the QC procedure, an AGV is always assigned to a charging spot if its battery level has dropped below 20% or if its battery level is less than 18 kWh (to prevent negative battery levels in the simulation when performing the maximum driving distance at the DDN). In that case, the AGV enters the global *GoCharging* queue in order to be able to drive to its selected charger. As this threshold has already been simulated by other researchers (see section 1.3), the main contribution of this study lies in the last highlighted PDL code: in case an AGV's battery level has dropped below 50% while no QCs and ASCs

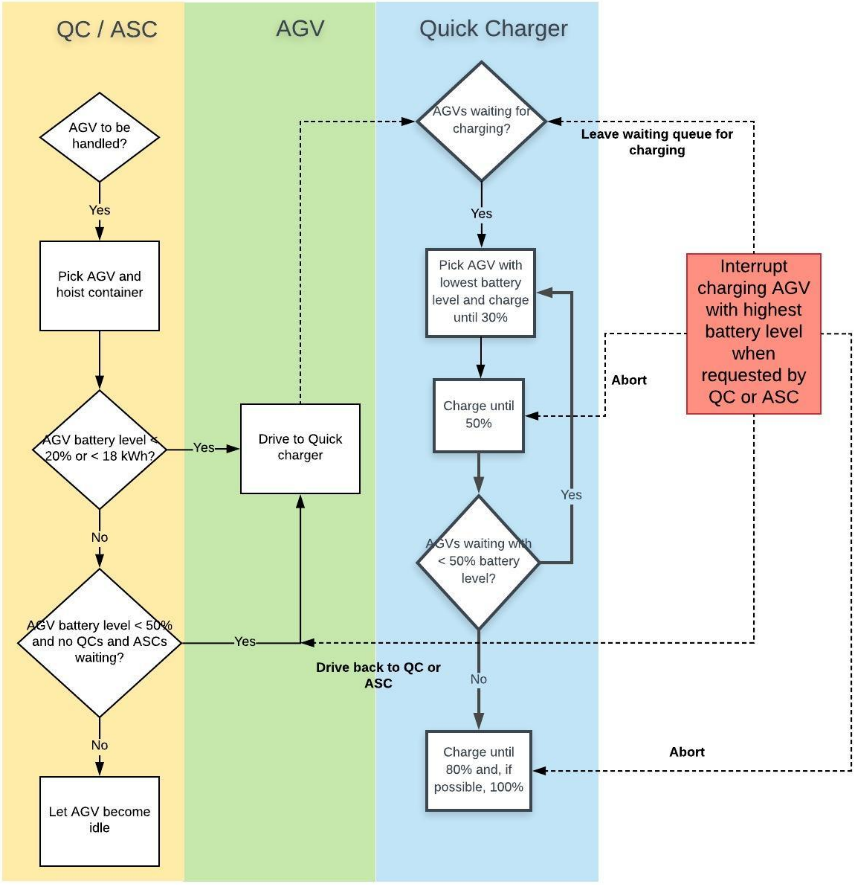


Figure 5.18: Charging procedure of electric AGVs after successful container handling

are requesting an AGV, the AGV is assigned the closest charger with maximally two other AGVs claiming this charging spot. Subsequently, the AGV enters the global *GoCharging* queue.
Likewise the QC procedure, the ASC procedure performs the same decision actions, with as only difference that the ASC first checks whether there are containers waiting in its own stack before deciding upon opportunity charging.

AGV

For the AGV procedure, instead of entering *GoTanking* the AGVs now enter *GoCharging* and *ChargingAGVs*, from which they can be picked by QCs and ASCs requesting AGVs. As driving to a charger is an empty trip, consequently (4.33*travel distance) kWh is subtracted from the battery level. When arrived at a charger, the AGV enters its *WaitingForCharging* queue, after which it is checked by the AGV if another AGV is still charging at the same spot. If so, its battery level is checked: if the battery level of the charging AGV is higher than 50% and the battery level of the AGV itself is lower than 50%, the charging AGV stops charging and enters the charger's *WaitingForCharging* queue again, while the arrived AGV starts charging. This modeling decision has been made in order to distribute battery capacity among all AGVs more equally.
Regarding the remaining adjustments, 7.09 kWh/km is applied as default energy consumption for loaded AGVs.

Charger

Instead of tanking stations, chargers are now used for refueling AGVs. Looking at the corresponding PDL model in Figure 5.23, it is repeatedly checked whether the charger's *WaitingForCharging* queue is filled with AGVs. If so, the AGV with the lowest battery level is selected charging; in case the AGV's battery level is below

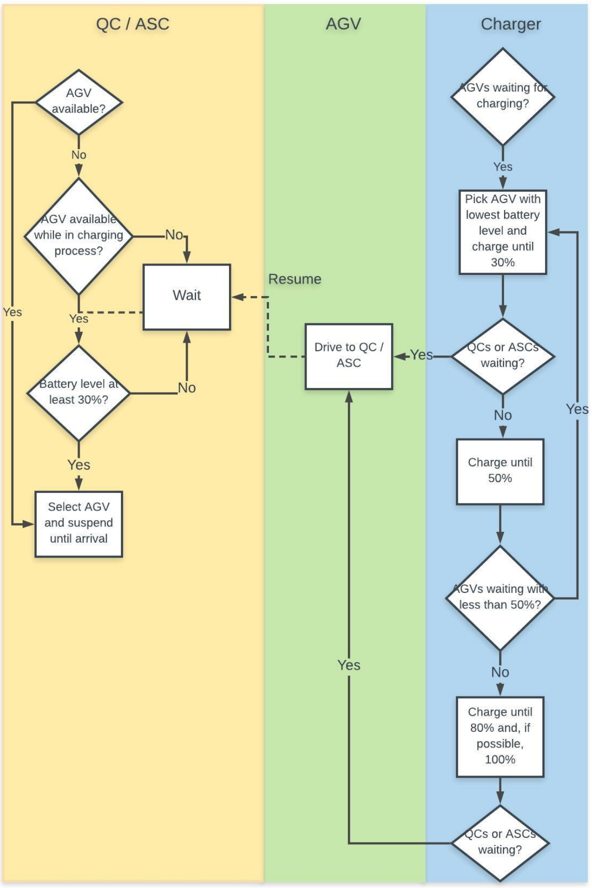


Figure 5.19: Request procedure of electric AGVs by QCs and ASCs

35%, its battery is charged until 35%. The time it takes to fully charge a battery with e.g. a capacity of 160 kWh is calculated with the following formula:

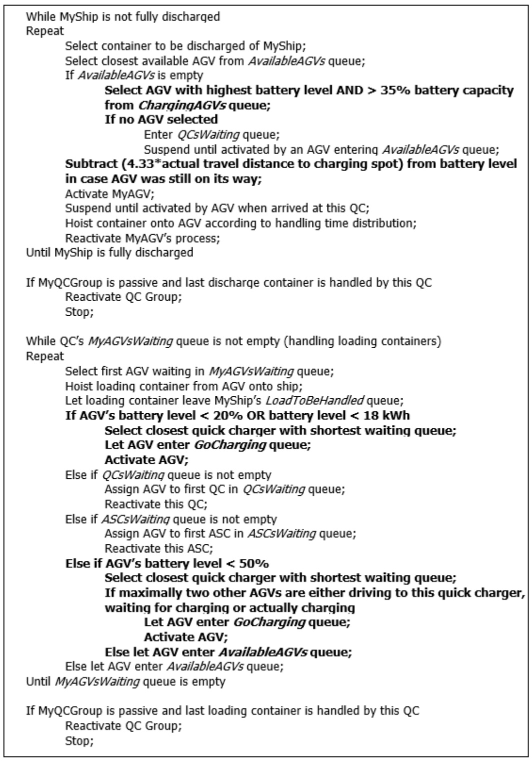
$$t_{charge}\,[\text{hours}] = \frac{0-80\%\,\text{of battery capacity [kWh]}}{\text{quick charging power [kW]} * \text{efficiency}} + \frac{80-100\%\,\text{of battery capacity [kWh]}}{\frac{1}{4} * \text{quick charging power [kW]} * \text{efficiency}} \tag{5.2}$$

The multiplying factor of $\frac{1}{4}$ resembles non linearity in charging a Lithium-Ion battery; as described in section 3.2, Kooten Niekerk et al. (2017) found that charging a Li-Ion battery from 80-100% takes approximately the same time as charging from 0-80%. Thereby, this multiplying factor accounts for slow charging. As an example, when a 160 kWh battery is being charged from 40% to 90% with a charging power of 300 kW and an efficiency rate of 97%, this will take ((0.8-0.4)*160/(300*0.97)) + ((0.9-0.8)*160/(0.25*300*0.97)) = 26.4 minutes.

Going back to the PDL model, when the AGV's battery level has reached 35%, the AGV becomes available for requests by QCs and ASCs. When charged until 50%, the charger procedure itself checks whether there are AGVs waiting for charging with a battery level lower than 50% (remind that this is double checked in the AGV procedure due to the nature of discrete event simulation). In case no AGVs with lower battery levels are waiting for charging, the charging AGV charges until 80% and, if possible, until 100%, after which the charger lets the AGV leave the global *ChargingAGVs* queue and enter *AvailableAGVs*.

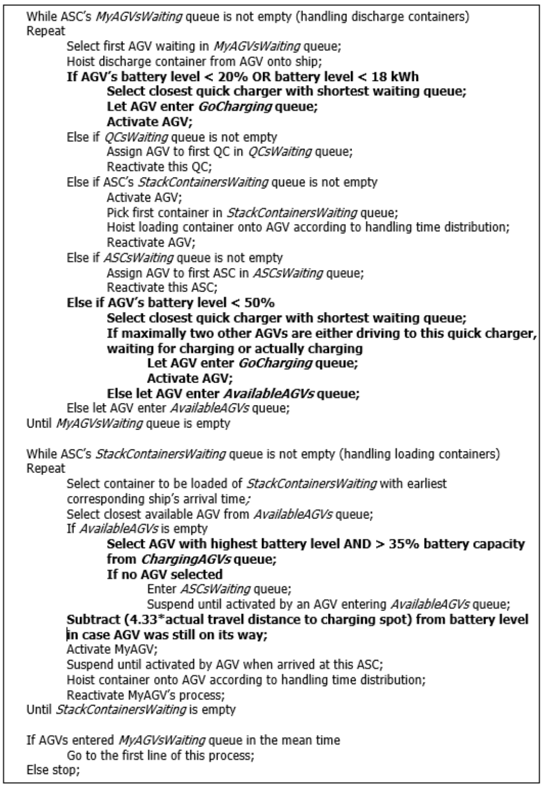
5.7.3. Verification and validation

Similar to the diesel AGV variant, the battery-electric AGV simulation model has been verified by using *Hand event tracing, Seed independence tests* and *Comparison with back-of-the-envelope calculations*. Appendix F elaborates further upon the execution and results of these verification steps; here, it suffices to inform the



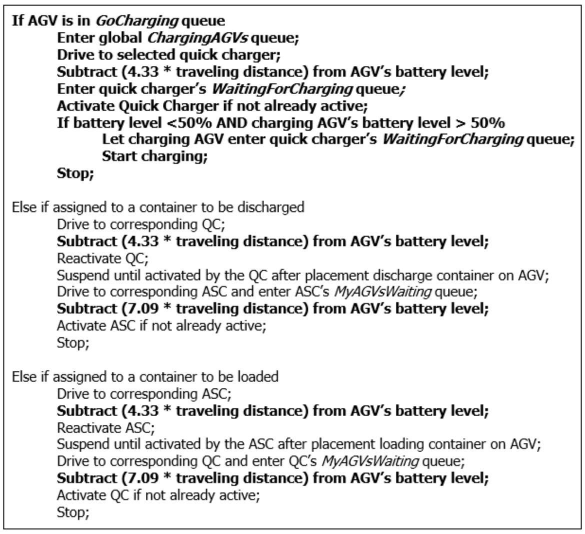
```
While MyShip is not fully discharged
Repeat
        Select container to be discharged of MyShip;
        Select closest available AGV from AvailableAGVs queue;
        If AvailableAGVs is empty
                Select AGV with highest battery level AND > 35% battery capacity
                from ChargingAGVs queue;
                If no AGV selected
                        Enter QCsWaiting queue;
                        Suspend until activated by an AGV entering AvailableAGVs queue;
        Subtract (4.33*actual travel distance to charging spot) from battery level
        in case AGV was still on its way;
        Activate MyAGV;
        Suspend until activated by AGV when arrived at this QC;
        Hoist container onto AGV according to handling time distribution;
        Reactivate MyAGV's process;
Until MyShip is fully discharged

If MyQCGroup is passive and last discharge container is handled by this QC
        Reactivate QC Group;
        Stop;

While QC's MyAGVsWaiting queue is not empty (handling loading containers)
Repeat
        Select first AGV waiting in MyAGVsWaiting queue;
        Hoist loading container from AGV onto ship;
        Let loading container leave MyShip's LoadToBeHandled queue;
        If AGV's battery level < 20% OR battery level < 18 kWh
                Select closest quick charger with shortest waiting queue;
                Let AGV enter GoCharging queue;
                Activate AGV;
        Else if QCsWaiting queue is not empty
                Assign AGV to first QC in QCsWaiting queue;
                Reactivate this QC;
        Else if ASCsWaiting queue is not empty
                Assign AGV to first ASC in ASCsWaiting queue;
                Reactivate this ASC;
        Else if AGV's battery level < 50%
                Select closest quick charger with shortest waiting queue;
                If maximally two other AGVs are either driving to this quick charger,
                waiting for charging or actually charging
                        Let AGV enter GoCharging queue;
                        Activate AGV;
                Else let AGV enter AvailableAGVs queue;
        Else let AGV enter AvailableAGVs queue;
Until MyAGVsWaiting queue is empty

If MyQCGroup is passive and last loading container is handled by this QC
        Reactivate QC Group;
        Stop;
```

Figure 5.20: Adjusted QC PDL model



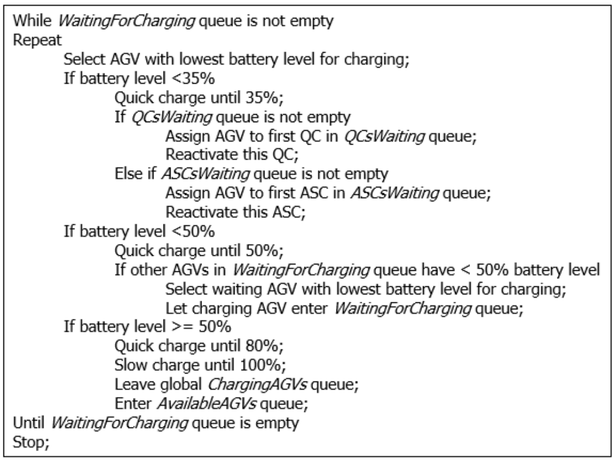
```
While ASC's MyAGVsWaiting queue is not empty (handling discharge containers)
Repeat
        Select first AGV waiting in MyAGVsWaiting queue;
        Hoist discharge container from AGV onto ship;
        If AGV's battery level < 20% OR battery level < 18 kWh
                Select closest quick charger with shortest waiting queue;
                Let AGV enter GoCharging queue;
                Activate AGV;
        Else if QCsWaiting queue is not empty
                Assign AGV to first QC in QCsWaiting queue;
                Reactivate this QC;
        Else if ASC's StackContainersWaiting queue is not empty
                Activate AGV;
                Pick first container in StackContainersWaiting queue;
                Hoist loading container onto AGV according to handling time distribution;
                Reactivate AGV;
        Else if ASCsWaiting queue is not empty
                Assign AGV to first ASC in ASCsWaiting queue;
                Reactivate this ASC;
        Else if AGV's battery level < 50%
                Select closest quick charger with shortest waiting queue;
                If maximally two other AGVs are either driving to this quick charger,
                waiting for charging or actually charging
                        Let AGV enter GoCharging queue;
                        Activate AGV;
                Else let AGV enter AvailableAGVs queue;
        Else let AGV enter AvailableAGVs queue;
Until MyAGVsWaiting queue is empty

While ASC's StackContainersWaiting queue is not empty (handling loading containers)
Repeat
        Select container to be loaded of StackContainersWaiting with earliest
        corresponding ship's arrival time;
        Select closest available AGV from AvailableAGVs queue;
        If AvailableAGVs is empty
                Select AGV with highest battery level AND > 35% battery capacity
                from ChargingAGVs queue;
                If no AGV selected
                        Enter ASCsWaiting queue;
                        Suspend until activated by an AGV entering AvailableAGVs queue;
        Subtract (4.33*actual travel distance to charging spot) from battery level
        in case AGV was still on its way;
        Activate MyAGV;
        Suspend until activated by AGV when arrived at this ASC;
        Hoist container onto AGV according to handling time distribution;
        Reactivate MyAGV's process;
Until StackContainersWaiting is empty

If AGVs entered MyAGVsWaiting queue in the mean time
        Go to the first line of this process;
Else stop;
```

Figure 5.21: Adjusted ASC PDL model



```
If AGV is in GoCharging queue
        Enter global ChargingAGVs queue;
        Drive to selected quick charger;
        Subtract (4.33 * traveling distance) from AGV's battery level;
        Enter quick charger's WaitingForCharging queue;
        Activate Quick Charger if not already active;
        If battery level <50% AND charging AGV's battery level > 50%
                Let charging AGV enter quick charger's WaitingForCharging queue;
                Start charging;
        Stop;

Else if assigned to a container to be discharged
        Drive to corresponding QC;
        Subtract (4.33 * traveling distance) from AGV's battery level;
        Reactivate QC;
        Suspend until activated by the QC after placement discharge container on AGV;
        Drive to corresponding ASC and enter ASC's MyAGVsWaiting queue;
        Subtract (7.09 * traveling distance) from AGV's battery level;
        Activate ASC if not already active;
        Stop;

Else if assigned to a container to be loaded
        Drive to corresponding ASC;
        Subtract (4.33 * traveling distance) from AGV's battery level;
        Reactivate ASC;
        Suspend until activated by the ASC after placement loading container on AGV;
        Drive to corresponding QC and enter QC's MyAGVsWaiting queue;
        Subtract (7.09 * traveling distance) from AGV's battery level;
        Activate QC if not already active;
        Stop;
```

Figure 5.22: Adjusted AGV PDL model



```
While WaitingForCharging queue is not empty
Repeat
        Select AGV with lowest battery level for charging;
        If battery level <35%
                Quick charge until 35%;
                If QCsWaiting queue is not empty
                        Assign AGV to first QC in QCsWaiting queue;
                        Reactivate this QC;
                Else if ASCsWaiting queue is not empty
                        Assign AGV to first ASC in ASCsWaiting queue;
                        Reactivate this ASC;
        If battery level <50%
                Quick charge until 50%;
                If other AGVs in WaitingForCharging queue have < 50% battery level
                        Select waiting AGV with lowest battery level for charging;
                        Let charging AGV enter WaitingForCharging queue;
        If battery level >= 50%
                Quick charge until 80%;
                Slow charge until 100%;
                Leave global ChargingAGVs queue;
                Enter AvailableAGVs queue;
Until WaitingForCharging queue is empty
Stop;
```

Figure 5.23: Adjusted Charger PDL model

reader that, likewise the diesel AGV version, all tests have been passed successfully which indicates that the model works according to the PDL specification.

Regarding the validation of the battery-electric AGV simulation model, to the author's knowledge no historical data is available, neither from the industry nor from the academic world. This study therefore serves as a first step in gaining insight into the operational feasibility of opportunity charging Lithium-Ion battery-electric AGVs at brownfield container terminals. Yet, it must be mentioned that the core structure of the simulation model, which remained unchanged in both the diesel AGV and electric AGV version, *is* valid as described in section 5.6. Since the behaviour of battery-electric AGVs in the simulation model turned out to be representative for the PDL specification, it is not expected that the simulation outcomes would significantly differ from actual data (if available).

5.8. Conclusion

This chapter aimed at providing the reader the methodology choice, model structure, verification and validation which forms the basis for the operational comparison of the selected design of the AGV charging process from the previous chapter, *opportunity plug-in charging at the ASC TPs*, to the current situation with diesel AGVs in order to answer the fourth subquestion of this study:

4. How do the selected designs of the AGV charging process influence the operational performance when compared to diesel AGVs?

Therefore, the model has been built for diesel AGVs by default, after which the model is adjusted and extended to the selected AGV charging design in section 5.7. The selected simulation software is Borland Delphi with TOMAS extension due to its process-oriented discrete event approach, which is especially useful for modeling simultaneous and interacting terminal operations. Main characteristic of modeling in TOMAS is the use of queues: interaction between terminal system elements is achieved by putting these elements (temporarily) in predefined queues by which they interact. For example, an AGV is able to enter a QC's specific *AGVsWaiting* queue once the AGV has arrived at the corresponding QC but still has to wait for other AGVs to be handled first. Consequently, various queues have been defined and used accordingly.

QCs, AGVs and ASCs form the core of the simulation model for which processes are defined for interaction purposes. Important to mention is that instead of actual physical driving of AGVs, an average speed has been applied which accounts for congestion on the AGV grid and interaction with other vehicles. The simulation model uses the equipment configuration and operations of the DDN side of the Delta Terminal which have been obtained by analyzing ECT data. Regarding model control, though, distributed control has been applied in the simulation model while in practice all terminal elements are centrally controlled by the TOS. Chosen is for distributed control over central control for the sake of modeling efficiency: instead of executing one central process over and over (with all decision logic included for all terminal equipment for all thinkable scenarios), only element specific processes are activated in case of interactions between equipment; the distributed control architecture is depicted in Figure 5.13.

After implementing the AGV tanking logic into the simulation model, the diesel AGV simulation model for the DDN and DDE has been verified and validated with actual ECT KPI data. The developed model works according its specification and produces outcomes which are close to actual ECT data. Consequently, the simulation model has been adjusted and extended to battery-electric AGVs by changing the fuel consumption of empty and loaded trips and by implementing the designed charging management strategies of Figures 5.18 and 5.19 for a battery-electric AGV fleet. The resulting battery-electric AGV simulation model has been verified only; to the author's knowledge no historical data on opportunity charging battery-electric AGVs at brownfield container terminals is available yet, neither from the industry nor from the academic world. This study therefore serves as a first step in gaining insight into the operational feasibility of opportunity charging battery-electric AGVs at brownfield container terminals.

The main output of this chapter are the simulation models developed by default for diesel AGVs and extended with battery-electric AGVs according to the selected AGV charging design which will be used in the next chapter for the assessment of the operational feasibility of replacing diesel AGVs by battery-electric AGVs at brownfield container terminals.

6

Simulation model application

This chapter aims to answer the fourth subquestion,
4. How do the selected AGV charging designs influence the operational performance when compared to diesel AGVs?
by experimenting with the developed simulation model for battery-electric AGVs from the previous chapter. More specifically, by using the diesel AGV simulation model as a reference, several parameters of the battery-electric AGV variant have been varied in order to test if a battery-electric AGV fleet becomes operationally feasible compared to the current state with diesel AGVs. Section 6.1 starts with the description of the experimental setup, in which run length, number of replications and chosen base case are explained. Section 6.2 summarizes the findings regarding the simulation model's sensitivity to changing uncertain input, after which section 6.3 presents and discusses the results of the conducted simulation experiments for the DDN. As a side experiment, the DDE has also been simulated and experimented with, however, this is elaborated upon extensively in Appendix I. Section 6.4 aims at providing an answer for one of this study's two main questions: "Is it operationally feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?", after which section 6.5 offers the reader insight into the robustness of the selected AGV charging process design regarding future increases in terminal throughput. Finally, this chapter ends with an overall conclusion. The main methodology used in this chapter is discrete event simulation. Figure 6.1 graphically shows the structure of this chapter with the main output and relations between the sections.

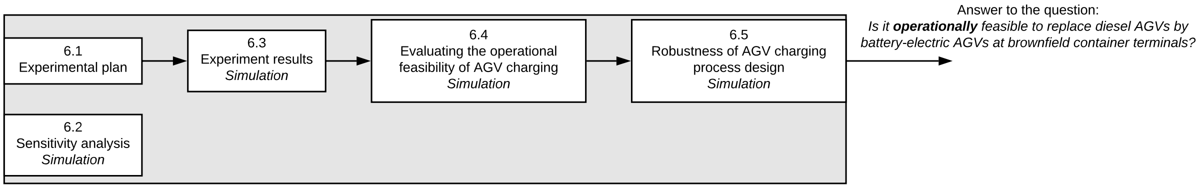


Figure 6.1: Structure, methods and output of Chapter 6

6.1. Experimental plan

Before experimenting with the developed simulation model for opportunity plug-in charging battery-electric AGVs at the ASC TPs, several aspects have to be determined, i.e. the *run length* of each experiment, the *base case* from where *which variables to vary on what range* and the *number of replications* per experiment, in order to obtain statistically robust results.

6.1.1. Run length

For the determination of the minimum run length, pilot simulations have been run in order to check for all KPIs when they reach a stable value. All KPIs reached a stable value after circa 25,000 time steps, except from the *percentage of QCs waiting for available AGVs*. Looking at Figure 5.17, it was repeatedly observed that a stable value was established after about 120,000 time steps. For battery-electric AGVs, as will be shown later on in this chapter, the warm-up period is even higher: 150,000 time steps. Therefore, it is decided to set the total run time on 210,000 time steps, in order to reduce the influence of the warm-up period (which is included in the simulation outcome). Regarding computational time, 210,000 time steps took approximately half an hour run time.

6.1.2. Battery-electric AGVs base case

Regarding the experimenting phase, one needs to have a base case from where to tune variables one after another in order to obtain the individual contribution/relation of each variable to the total simulation outcome. As the main objective of this chapter and of the developed simulation model for battery-electric AGVs is to find out if electric charging is operationally feasible at brownfield terminals in general and at the ECT Delta Terminal in particular, variables influencing the operational performance of electric vehicles have been consequently looked up in literature. Schmidt et al. (2014) and Schmidt et al. (2015) mention that *battery capacity* is of influence on the operational performance of battery-electric AGVs. McHaney (1995) mentions the speed of charging or charger size and the *amount and location of charging spots*; within this study's context, charger size or speed of charging is operationalized into the *charging power* of chargers in kilowatt. The number of battery-electric AGVs is added as variable as this determines to a large extent the operational performance of container terminals in general. Finally, not mentioned in literature but interesting for this research is the defined *opportunity charge threshold* of the implemented charging management strategy depicted in Figures 5.18 and 5.19. This threshold value has been added to avoid too frequent charging trips of AGVs, which leads to energy inefficiency. As a default, 50% is chosen: AGVs are allowed to opportunity charge their batteries when their battery level is equal or lower than 50%. However, it can be argued that varying this threshold value will impact AGV operations: setting this value for example to 20% switches opportunity charging into conventional charging below the 20% threshold value. This might have negative impact on the operational performance as all AGVs may need to charge their batteries at the same time which will lead to (long) waiting queues. On the contrary, setting this threshold value higher creates a temporal buffer for AGVs to charge their batteries, thus potentially improving AGVs' operational performance. In order to evaluate this relation, the AGV opportunity charge threshold has been added to the experimental plan.

Consequently, the base case as shown in Table 6.1 is used for the DDN side of the Delta Terminal. Regarding the number of AGVs, the same amount as the current number of AGVs driving at the DDN is chosen to be the base case in order to assess the logistical impact of a battery-electric AGV fleet without an increase in the number of vehicles. For the battery capacity, 160 kWh is chosen as a base as this is a wide industry standard; Kalmar, VDL, ZPMC and Konecranes/Gottwald all have installed batteries of approximately this size in their AGVs (Kalmar, 2018; ZPMC, 2018). Synthesizing from section 3.3.1, the average charging power currently available on the market lies somewhere around 300 kW; therefore, this value is chosen as the base case. For the latter two variables, no suggestion was given on beforehand as there is no earlier work on the amount of chargers needed for battery-electric AGVs, let alone the threshold at which AGVs are able to opportunity charge their batteries. Therefore, pilot simulations were run; the outcomes showed that 6 chargers were approximately sufficient to avoid large differences compared to the diesel AGV base case.

Regarding the variables to be varied, one important variable is missing: the *location* of the charging spots. According to the selected design of the AGV charging process, opportunity plug-in charging at the ASC TPs, chargers are evenly distributed on the ASC TPs along the whole longitudinal space at stack side, which' design space is highlighted in green in Figure 6.2.

Finally, a proper range around the base case is defined in order to sufficiently assess the individual effect of each variable to the total simulation outcome.

Table 6.1: Base case for the DDN with the variables to be varied and the variation range

	Base case DDN	**Range DDN**
Number of AGVs [#]	65	[35, 50, 65, 80, 95]
Battery capacity [kWh]	160	[60, 100, 160, 220]
Charging power [kW]	300	[100, 150, 200, 300, 600]
Number of charging spots	6	[2, 3, 4, 6, 8, 12]
AGV opportunity charge threshold [%]	50	[30, 50, 60, 70]

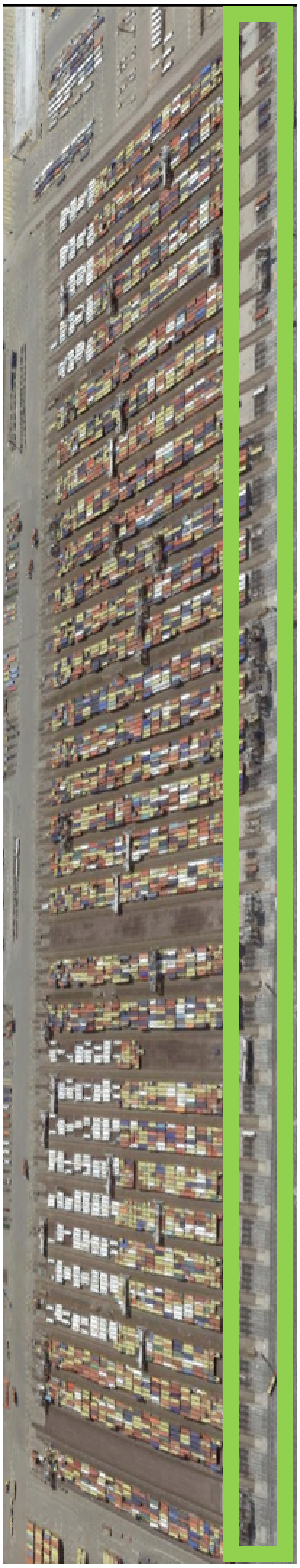


Figure 6.2: Layout of the stack side at the DDN with the physical design space for charging highlighted in green

6.1.3. Number of replications

Finally, one needs to determine the number of replications to be performed per experiment. Hoad et al. (2007) synthesize the three main methods found in literature: *Rule of Thumb*, *Graphical Method* and *Confidence Interval Method*. Whereas the Rule of Thumb suggests the experimenter to perform 3 to 5 replications to require accuracy in the simulation outcomes, Graphical Method first plots the cumulative mean of a selected output variable against the number of replications and then checks where the obtained line becomes flat, i.e. approaches the asymptotic cumulative mean. However, for this study the Confidence Interval Method is chosen for the determination of the number of replications. Hoad et al. (2007) describe in their synthesis that the minimum amount of replications is three. The precision level is calculated by:

$$\text{Precision level of Hoad et al. (2007)} = \frac{\frac{1}{2} * \text{confidence interval}}{\text{cumulative mean}} * 100\% \tag{6.1}$$

where the precision level is calculated for a selected output variable; in this study the selected output variable is chosen to be the turnaround time of MAIN ships, as this variable must be accurately enough be determined for later use in the TCO analysis. Also, a desired precision level must be determined; Hoad et al. (2007) use a precision level of 5% which is also used in this study. By repeating each experiment three times - that is done by changing input seeds - the precision level can be calculated according to equation 6.1. Whenever this precision is lower than the desired precision level, the number of replications is set at 3. If the precision level turns out to be higher or equal to the desired precision level, extra replications must be performed; Hoad et al. (2007) advise an additional amount of replications of 5. The confidence intervals and cumulative means of the MAIN turnaround times for each experiment have been calculated using SPSS.

6.2. Sensitivity analysis

Before experimenting with the developed model, a sensitivity analysis is performed in order to assess changes in input values on simulation outcomes. Consequently, *AGV fuel consumption* and *AGV speed* have been increased and decreased with 25% for both the diesel and battery-electric AGV version to test whether this causes large variations in model output. Main reason for changing these variables only are the way in which they were obtained: AGV fuel consumption has been calculated by hand and AGV speed was retrieved from a large data set which was sensitive to differences in entrance points into the QC lanes. Given the uncertainty regarding the actual value, Tables 6.2 and 6.3 offer the reader the results of this analysis, which is performed for both the diesel and battery-electric AGV version of the DDN simulation model.

6.2.1. AGV speed versus terminal productivity

AGV speed negatively correlates with the ship turnaround times, which was expected as AGVs are able to handle more containers per hour with a higher speed. However, the reader is reminded that this speed comprises the overall average speed instead of the maximum speed of the AGV. Since no interactions between AGVs *during driving* have been modeled, no congestion occurs (this is included in the average speed), thus no conclusions can be drawn regarding ECT's wish to increase its future AGV fleet's speed. This observed relation merely serves as an extra verification of the developed models, as higher speeds lead to higher quay throughputs (i.e. higher QC productivity). Also, changes in AGV speed turn out to have a strong influence on the main terminal KPIs, such as turnaround times, productivity and equipment utilizations. Therefore, ECT and other terminal operators around the world opt for a vehicle fleet which is as small as possible in order to avoid congestion on the AGV grid.

6.2.2. AGV fuel consumption versus terminal productivity

In contrast to AGV speed, AGV fuel consumption does not correlate strongly with the most important terminal KPIs. Subsequently increasing and decreasing AGV fuel consumption with 25% showed not have an influence on the ship turnaround times, productivity and utilization rates. For diesel AGVs, this can be explained by the amount of trips that can be performed on a single tank. When considering the base scenario with 1.10 liters/empty kilometer and 1.80 liters/loaded kilometer and knowing that handling one container on average takes 800 meters traveling distance (retrieved from data analysis of ECT tank data, 400 meters empty and 400 meters loaded), the total number of containers that can be handled with a full tank - i.e. 1200 liters - is equal to 1200/(1.1*0.4 + 1.8*0.4) = 1034 containers per AGV. An increase and decrease of 25% causes this value to respectively drop and increase to 828 and 1379 containers per AGV, which is still more than enough to handle a single MAIN on time (given that there are 65 AGVs driving on the DDN).

Table 6.2: Sensitivity analysis results for the diesel AGV simulation model

	Base case	+25% AGV speed	-25% AGV speed	+25% AGV fuel consumption	-25% AGV fuel consumption
Turnaround time MAIN [minutes]	856	832	911	857	856
Turnaround time BARGE [minutes]	232	229	239	234	232
QC productivity [mvs/hour/QC]	22.97	23.30	22.02	22.80	22.91
QC utilization rate [%]	76.4	77.5	73.3	75.9	76.3
AGV utilization rate [%]	79.5	79.8	77.1	78.9	78.9
Percentage of QCs waiting for AGVs [%]	26.5	26.7	23.7	26.2	26.5
Average waiting time QCs for AGVs [seconds]	122	101	149	121	122
Empty AGV trip fraction [%]	43.6	43.0	42.1	42.6	42.7

Table 6.3: Sensitivity analysis results for the battery-electric AGV simulation model

	Base case	+25% AGV speed	-25% AGV speed	+25% AGV fuel consumption	-25% AGV fuel consumption
Turnaround time MAIN [minutes]	867	838	929	869	866
Turnaround time BARGE [minutes]	239	234	240	237	238
QC productivity [mvs/hour/QC]	22.58	23.08	21.69	22.55	22.62
QC utilization rate [%]	75.2	76.9	72.2	75.1	75.3
AGV utilization rate [%]	80.9	81.6	78.3	81.2	80.4
Percentage of QCs waiting for AGVs [%]	28.8	29.8	26.0	28.5	27.8
Average waiting time QCs for AGVs [seconds]	127	106	155	127	125
Empty AGV trip fraction [%]	46.9	47.2	46.5	47.9	46.1

When looking at battery-electric AGVs, the amount of containers that can be handled with a full battery is, given the base case with 160 kWh batteries, equal to 160/(4.33*0.4 + 7.09*0.4) = 35. A 25% increase and decrease of the AGV energy consumption causes this amount to respectively drop and increase to 28 and 47 containers per AGV. Apparently, opportunity charging in between two transport jobs compensates for this lower container handling capacity, as this is observed from the empty AGV trip fractions. Looking at diesel AGVs, the empty ride fractions of both the 25% increase and decrease in AGV fuel consumption are approximately the same. For battery-electric AGVs, though, these values almost differ with 2%, which can be explained by the frequency with which AGVs drive to a charging spot: a higher energy consumption causes AGV batteries to be charged more frequently, thus performing relatively more empty AGV rides.
Concludingly, it is stated that an increase in average AGV speed will be more effective in improving *logistical* terminal performance than making AGVs more energy efficient.

6.3. Experiment results

This section discusses the results of the experiments conducted for the DDN. The base case results for diesel AGVs as shown in Table 6.2 is included in all experiments as a reference to visualize the deterioriation in terminal performance when making the transition towards a full electric AGV fleet. Furthermore, a fixed charging efficiency of 97% is applied throughout the experiments; decided is not to vary this value as, in consultation with Kalmar, ZPMC and Heliox, 95%-97% is the industry's standard (see Appendix J for the reference). The number of AGVs, battery capacity, charging power, number of charging spots and opportunity charge threshold is varied one by one according to the ranges defined in Table 6.1. The results of these experiments are discussed in the following paragraphs.

Number of AGVs

Starting with the number of AGVs, 5 experiments were conducted which were repeated three times to obtain the required level of precision. The outcomes are presented in Figures 6.3 and 6.4; it is observed that increasing the number of battery-electric AGVs to 75-80 leads to an equal turnaround time compared to diesel AGVs. However, for 65 AGVs the difference in MAIN turnaround time is already very small (11 minutes). The convex shape of the TAT curves also show that further increasing the number of AGVs does not improve terminal performance significantly as the QC capacity starts to function as the constraining factor (limited number of moves per hour due to manual operation).
Regarding the other KPIs, the same conclusions are drawn; much gain is made in increasing the number of

AGVs from 35 to 65, though, when further increasing the number of AGVs no significant increase in QC utilization or percentage of QCs waiting is perceived. Also, the QC productivity curve starts to flatten at this point.

A final remark is made on the average DoD of the AGVs: the parabolic curve, although very flat, is in line with intuition as a lower number of AGVs increases the probability that a charging spot is free for an AGV to drive to for opportunity charging while a higher number of AGVs reduces the probability of an individual AGV being requested by a QC or ASC immediately after finishing its last job. This latter reasoning results in AGVs driving to a charging spot at a higher battery level than in case less AGVs (i.e. 65) are driving on the DDN.

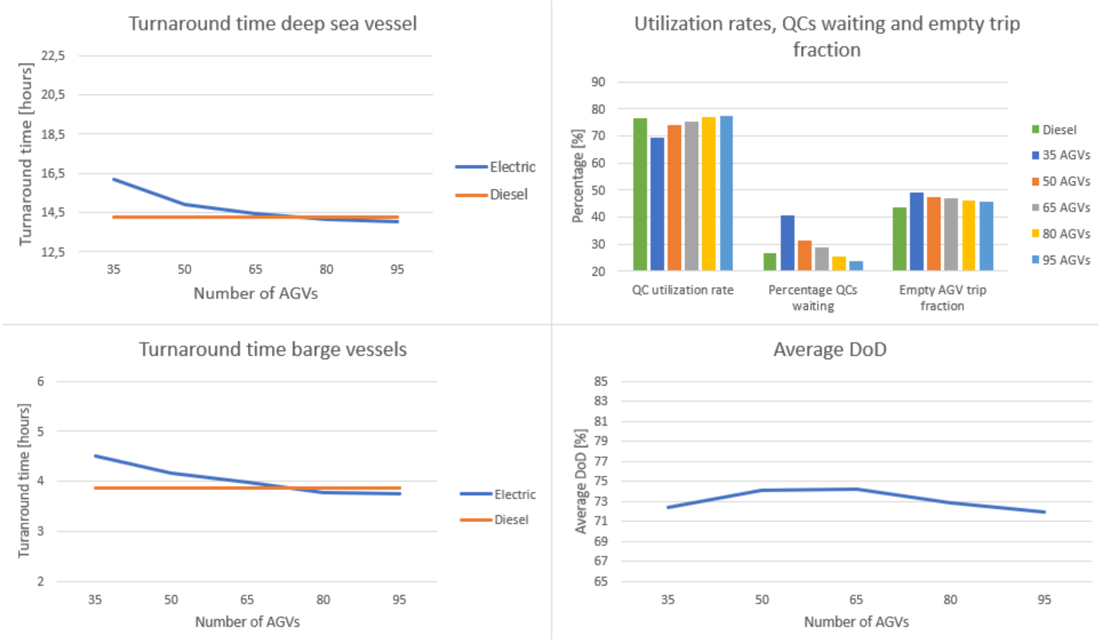


Figure 6.3: Various KPI values for a battery-electric AGV fleet of various sizes at the DDN; the diesel base case outcomes are included as a current state reference

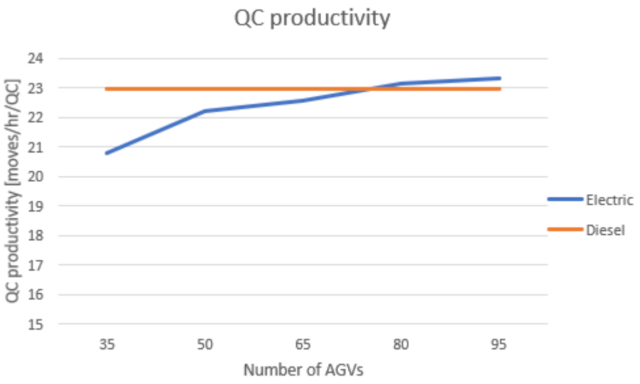


Figure 6.4: QC productivity of a battery-electric AGV fleet of various sizes at the DDN compared to diesel AGVs

Battery capacity

With regard to the battery capacity, four experiments were conducted which were repeated three times. Figures 6.5 and 6.6 show the results; it is immediately noticed that changes in battery capacities do not influence terminal performance. All KPIs - TATs, utilization rates and productivity - stay approximately the same when varying over the defined range. Apparently, AGVs compensate lower battery capacities with more frequent opportunity charging, as this can be noticed from the empty AGV trip fractions: 60 kWh batteries result in an empty trip fraction of almost 50% while 220 kWh batteries set this fraction at 46%. More importantly, frequent charging trips do not appear to result in terminal performance deterioration, which can be explained by Figure 2.8: in this figure, the average idle, waiting and active times of AGVs in between two transport cycles are depicted. As can be seen, idle and waiting times during and after a transport job take up a significant share in the total time, thereby having enough time for opportunity charging. This is also confirmed by the average charging time of AGVs obtained from the TOMAS Queues output window. This charging time, averaged over all 6 chargers (i.e. the base case), is equal to 11.04 minutes, which approaches the idle times obtained from Figure 2.8 and the idle time estimates of ECT experts (circa 15 minutes).

Looking at the average DoD, again a parabolic curve is observed, yet for different reasons. A battery capacity of 60 kWh results in AGVs go charging earlier due to the threshold applied in the simulation model. For the DDN, this threshold is set at 18 kWh in order to be able to perform a trip from and to the outer sides of the AGV area according to equation 5.1. As AGVs always go charging when reaching this threshold value, AGVs with 60 kWh batteries consequently have a maximum DoD of (1 - 18/60)*100% = 70%. From the graph, it is seen that AGVs on average even go charging earlier: whenever the opportunity arises. Looking at large battery capacities of 220 kWh, the DoD also decreases due to the fact that the batteries are now larger, which increases the probability that AGVs go charging at a higher battery level regardless of the terminal activities (which showed to have no correlation).

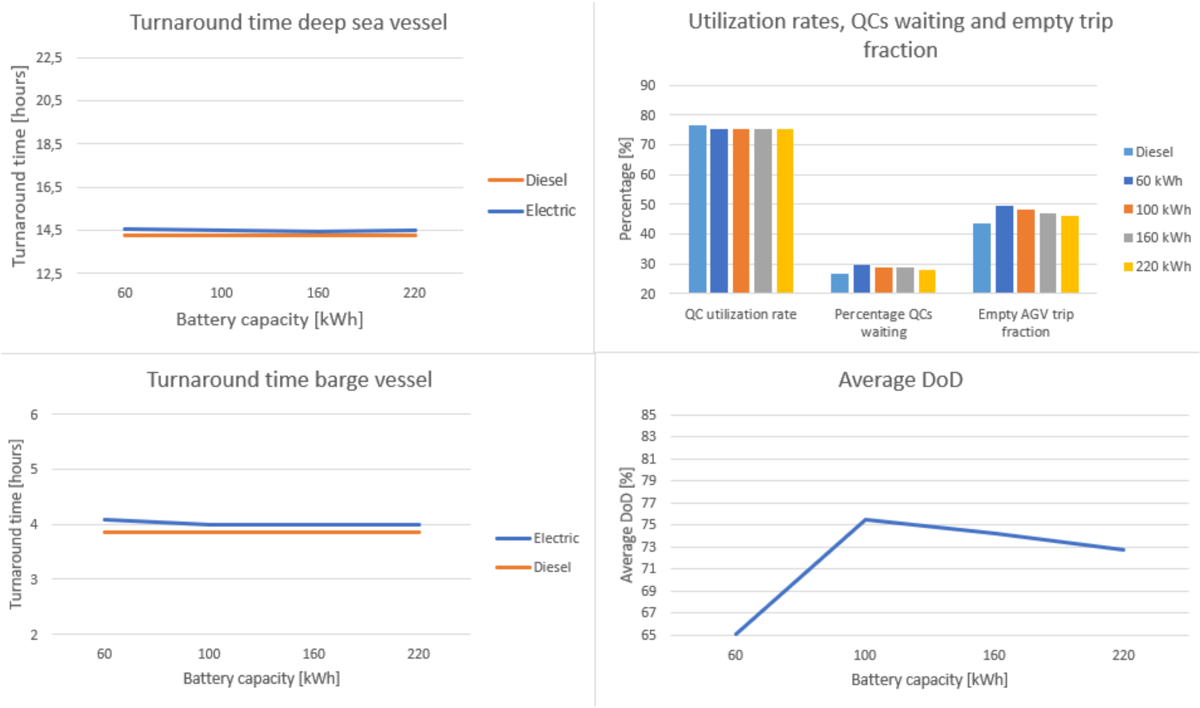


Figure 6.5: Various KPI values for a battery-electric AGV fleet with different battery capacities at the DDN; the diesel base case outcomes are included as a current state reference

Charging power

The relation between charging output power and terminal performance is visualized in Figures 6.7 and 6.8. As can be seen, a significant gain in terminal performance is made when increasing the charging power from 100 kW to 150 kW, after which the TATs, QC productivity and utilization rates slowly further increase with increasing power. This convex relation can most likely be explained by the idle time of AGVs in between two jobs. Figure 5.17 shows the average idle time of diesel AGVs before being requested for a new job; in this figure this is perceived by looking at the *average WT* of the *AvailableAGVs* queue. AGVs stay within this queue - and thus idle - for 14.84 minutes on average. Looking at Table 6.4, where the average charging durations of AGVs per charge at different charging output powers is obtained from simulation, these charging times

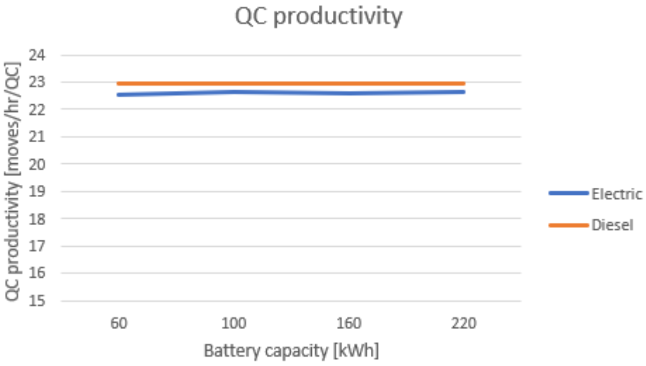


Figure 6.6: QC productivity of a battery-electric AGV fleet with different battery capacities at the DDN compared to diesel AGVs

count up to maximally 14 minutes: including driving time to the charging spot this approaches the diesel AGV idle time. What can thus be concluded is that, at minimum for the DDN, 35 kWh is needed per charge to approach the diesel AGV terminal performance; 23.3 kWh per charge turns out to be insufficient. As charging power increases, the average charging time decreases due to the priority rule implemented in the simulation: whenever an AGV is charged until 50% and other AGVs are waiting for charging with less than 50% battery level, the charge stops and the next AGV with the lowest battery level is selected for charging. Therefore, with higher charging speeds this threshold will be reached faster.

With regard to the average DoD, obviously DoD decreases when charging power increases as AGVs are being charged faster. This increases the probability that a charging spot is empty and can be effectively claimed by an AGV having a lower DoD than when a charging output power of 100 kW would have been applied (which would lead to very high charger utilization rates). Higher charging powers are thus desired in order to increase the battery lifetime, i.e. decrease average DoD.

Table 6.4: Average charging times and quantities at different output powers for the DDN

	100 kW	**150 kW**	**200 kW**	**300 kW**	**600 kW**
Average opportunity charge time [minutes]	14.0	14.1	12.7	11.0	8.3
Charged electric energy per charge [kWh]	23.3	35.3	42.3	55.0	83.0

Number of charging spots

One of the most important knowledge gaps currently existing among industry players is the amount of chargers that must be purchased in order to achieve equal terminal performance as with diesel AGVs. The outcomes of these experiments are shown in Figures 6.9 and 6.10; a steep decrease in TATs and steep increase in QC productivity and utilization rates can be observed when increasing the amount of chargers from 2 to 3, whereafter the performance further improves with increasing numbers of chargers (although very marginally). Apparently, 3 chargers suffice on a vehicle fleet size of 65 AGVs. From this study's side experiment, the DDE side of the Delta Terminal, which is elaborated upon extensively in Appendix I, it will become clear that this ratio of 1 charger to approximately 20 AGVs also holds for larger deep sea terminals with larger fleet sizes. However, an explanation can already be given, which is in close relation with Table 6.4: this table provided a minimal charging quantity that must be provided per charge in order to approach the diesel AGV terminal performance. From this table, it was concluded that approximately 35 kWh suffices; when looking at the charging times of both the scenarios with 2 and 3 chargers shown in Figures G.2 and G.3 in Appendix G, the average charging times are 4.66 and 7.30 minutes respectively. When converting these charging times into charging quantities given a charging power of 300 kW, the electrical energy charged per charge is equal to 23.3 kWh and 36.5 kWh respectively. As a consequence, 2 chargers do not suffice while 3 chargers are sufficient (> 35 kWh).

Regarding the average DoD, the shape of the curve is in line with intuition: as the number of chargers, which are evenly distributed over the ASCs, increases, the probability of a free charging spot for an AGV that wants

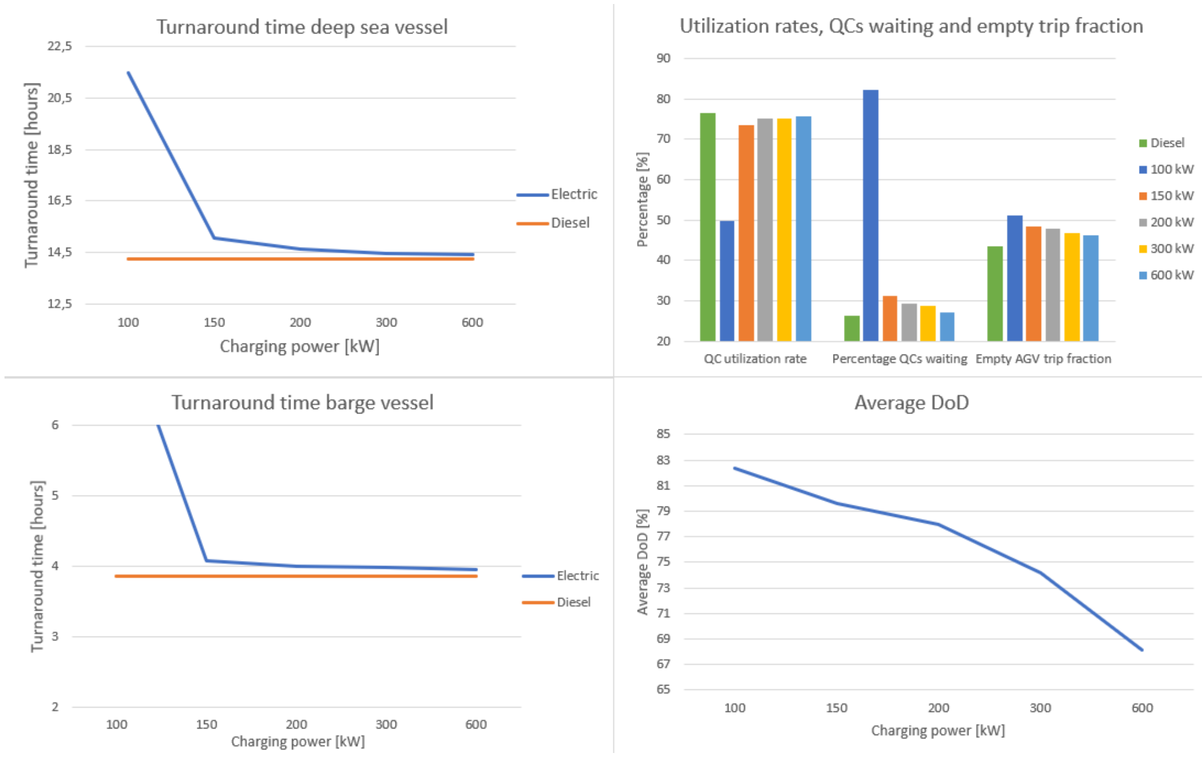


Figure 6.7: Various KPI values for a battery-electric AGV fleet with different charging powers at the DDN; the diesel base case outcomes are included as a current state reference

to charge becomes higher, which results in a lower DoD.

AGV opportunity charge threshold

The main focus of this simulation study is on opportunity charging; instead of charging AGVs at 20% the AGVs are charged whenever the opportunity arises. In the simulation, as a default 50% is chosen as minimum battery level from where AGVs are allowed to go charging; this is determined in order to reduce the amount of trips to a charger while maintaining space for opportunity charging. When varying with this threshold, no irregularities in simulation outcomes were found, as is shown in Figures 6.11 and 6.12. A possible explanation could be the fact that AGVs never simultaneously drop to a battery level lower than 30%, which would cause long waiting queues for charging spots. Thereby, AGVs searching for a charging spot will always be distributed over time, which is the core of the simulation logic, where AGVs are (1) charged more evenly (until 50%) and (2) requested by QCs/ASCs fairly by selecting the AGV with the highest battery level.
Looking at the DoD curve, a higher opportunity charge threshold logically results in lower DoDs as AGVs are allowed to charge at a higher battery level.

6.4. Evaluating the operational feasibility of AGV charging

As one of the two main objectives of this study is to find out if replacing diesel AGVs by battery-electric AGVs at brownfield container terminals is operationally feasible, this section is dedicated to this question. When looking at the graphs obtained for all tuned variables, i.e. number of AGVs, battery capacity, charging power, number of charging spots and opportunity charge threshold, it is seen that:

- approximately 75 battery-electric AGVs result in equal operational performance when compared to 65 diesel AGVs *given the base case configuration of 160 kWh battery capacity, 300 kW charging power and 6 charging spots.*
- battery capacity is not of influence on terminal performance *given the base case configuration of 65 AGVs, 300 kW charging power and 6 charging spots*

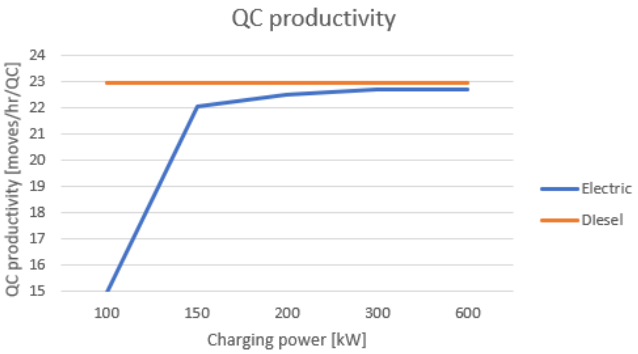


Figure 6.8: QC productivity of a battery-electric AGV fleet with different charging powers at the DDN compared to diesel AGVs

- a charging power of approximately 300 kW leads to minimal deterioration in operational performance *given the base case configuration of 65 AGVs, 160 kWh battery capacity and 6 charging spots.*
- 6 charging spots are approximately sufficient for minimal operational downtimes *given the base case configuration of 65 AGVs, 160 kWh battery capacity and 300 kW charging power.*

The design configuration of **75 AGVs, 160 kWh battery capacity, 300 kW charging power and 6 charging spots** has consequently been selected for further evaluation on its robustness for future growth in container transport. For the current state, it is concluded, looking at Table 6.5, that the selected AGV charging design meets the first requirement, *Incorporating the AGV charging process into the operational process should lead to equal operational performance compared to the current diesel AGV fleet*, as all simulation outcomes for battery-electric AGVs are roughly the same compared to a diesel AGV fleet.

Table 6.5: Simulation outcomes of the configuration [75 AGVs, 160 kWh battery capacity, 300 kWh charging power and 6 charging spots] for the DDN

	Diesel AGV fleet	**Battery-electric AGV fleet**
MAIN turnaround time [hours]	14.3	14.3
BARGE turnaround time [hours]	4.0	4.0
QC productivity [moves/hr/QC]	23.0	23.0
QC utilization rate [%]	76.4	76.3
Percentage of QCs waiting for AGVs [%]	26.5	27.3
Average waiting time QCs for AGVs [seconds]	122	123
Empty AGV trip fraction [%]	43.6	47.1

6.5. Robustness of the AGV charging process design

While all previous simulation runs conducted resembled ECT's current state with corresponding throughput, it is of main importance to test whether battery-electric AGVs are a robust solution for future growth in terminal throughput. Therefore, a scenario analysis is conducted in which:

1. QC capacities have been subsequently increased with 20% and 40%
2. ship call sizes have been subsequently increased with 20% and 40%

for both battery-electric and diesel AGVs at the DDN to test whether the relative difference in terminal KPIs remain approximately the same when compared to the current situation. The configuration as described in the previous section, 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 charging spots, has been used for the battery-electric AGV variant; for diesel AGVs, the reference case with 65 AGVs is used. Table 6.6 presents the results of this analysis; all scenarios have been repeated three times to obtain the required level of precision. It is observed that when increasing the capacity of the QCs by reducing its handling time with 20% and 40%, for both diesel and battery-electric AGVs this will result in a significant increase in productivity.

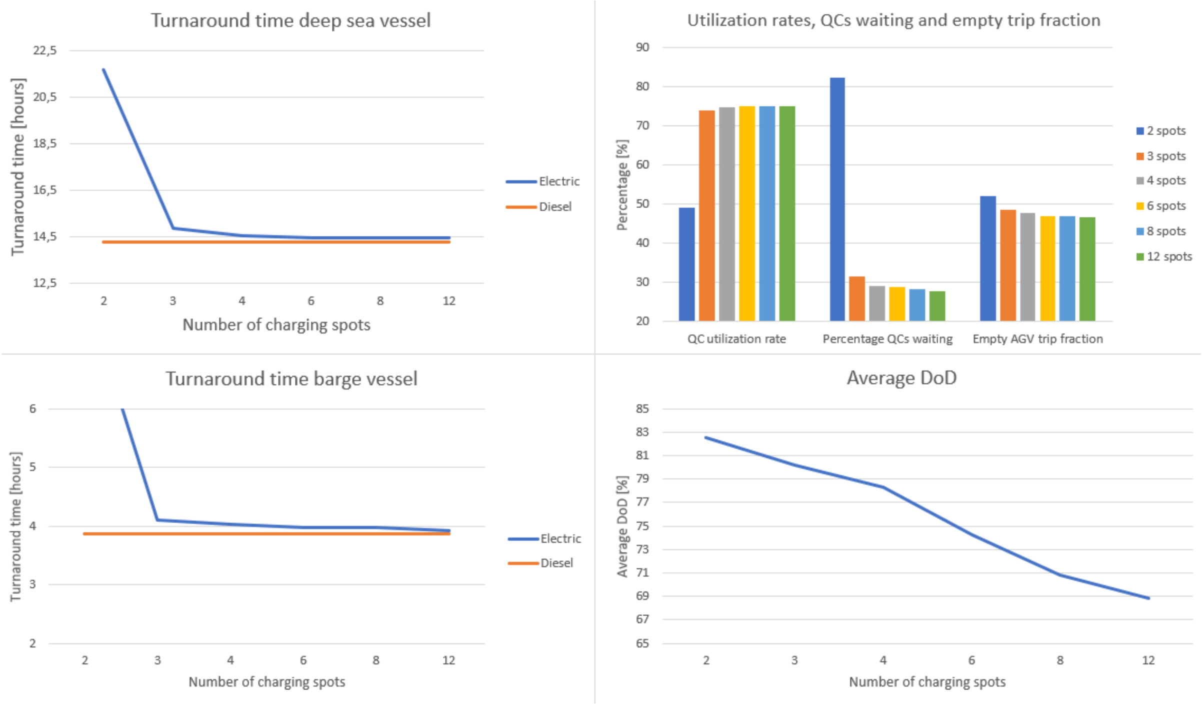


Figure 6.9: Various KPI values for a battery-electric AGV fleet with various amounts of chargers installed along the ASCs at the DDN; the diesel base case outcomes are included as a current state reference

When effectively reducing the QC handling times with 40%, it is even shown that QC productivity reaches 37 moves/hour with battery-electric AGVs, an increase of 60%. When looking at an increase in fleet size of 40% (from 65 to 91 AGVs), depicted in Figure 6.4 within the range 35-95 AGVs, an increase in productivity of only 4.5% occurs. Adding 30 AGVs to the current fleet thus has a marginal effect on the productivity of the terminal when compared to reducing the handling time of a QC when an AGV is on its TP. Thereby, it is highly recommended to focus on reducing actual QC handling times rather than improving the AGV-QC interaction in order to be resilient for future container transshipment growth.

Also, the scenarios in which MAIN and BARGE call sizes grow with 20% and 40% do not indicate significant differences in terminal performance between a diesel AGV and battery-electric AGV fleet. The relative differences in turnaround times, productivities and utilization rates are the same when compared to the current situation, i.e. the base case. It can thus be concluded that battery-electric AGVs prove to be a robust solution which are resilient to future growth in container throughput, given that they perform relatively equal to the current diesel AGV fleet in all growth scenarios.

6.6. Conclusion

This chapter aimed at answering the fourth subquestion,

4. How does the selected AGV charging design influence the operational performance when compared to diesel AGVs?

by experimenting with the developed simulation model for battery-electric AGVs from the previous chapter. More specifically, by using the diesel AGV simulation model as a reference, several parameters of the battery-electric AGV variant have been varied in order to test if a battery-electric AGV fleet becomes operationally feasible compared to the current state with diesel AGVs.

Experimental plan

Before experimenting with the simulation model, an experimental plan is made: five variables are selected for variation throughout the experiments: *number of battery-electric AGVs, battery capacity, charging power, number of chargers* and *the maximum battery level at which AGVs are allowed to opportunity charge.* The

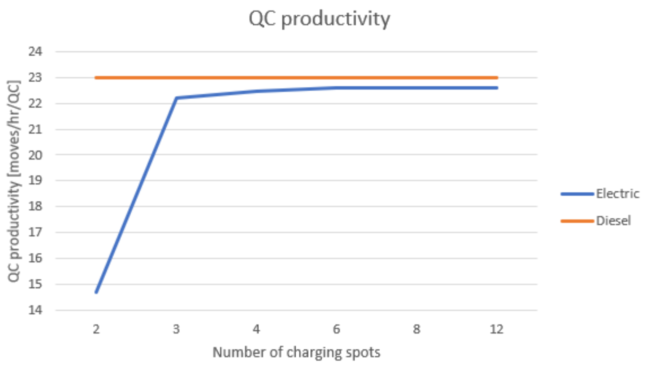


Figure 6.10: QC productivity of a battery-electric AGV fleet with different numbers of chargers at the DDN compared to diesel AGVs

Table 6.6: Simulation outcomes of future growth scenarios for the DDN

	Diesel AGV fleet					**Electric AGV fleet**				
	Current state	-20% QC handling time	- 40% QC handling time	+ 20% ship call sizes	+ 40% ship call sizes	Current state	- 20% QC handling time	- 40% QC handling time	+ 20% ship call sizes	+ 40% ship call sizes
MAIN turnaround time [hours]	14.3	12.3	10.2	16.4	18.6	14.3	12.2	10.1	16.4	18.5
BARGE turnaround time [hours]	4.0	3.1	2.4	4.5	5.4	4.0	3.1	2.4	4.5	5.4
QC productivity [moves/hr/QC]	23.0	28.2	36.9	22.2	21.4	23.0	28.2	37.0	22.3	21.5
QC utilization rate [%]	76.4	75.1	74.0	74.0	71.1	76.5	75.3	74.1	74.1	71.4
Percentage of QCs waiting for AGVs [%]	26.5	21.9	14.5	32.9	35.7	26.9	22.5	15.1	33.7	36.4
Average waiting time QCs for AGVs [seconds]	122	114	103	127	128	123	116	105	129	130
Empty AGV trip fraction [%]	43.6	42.3	41.8	42.9	43.1	46.7	46.3	45.9	47.1	47.5

operational design criteria on which the experiments are assessed are *vessel turnaround times, QC productivity, QC utilization rate, percentage of QCs waiting for AGVs, average waiting time of QCs* and the *empty AGV trip fraction*. In order to be able to deduct the individual relation between each variable and the terminal KPIs, a base case is defined for the DDN from where the variables are varied over a predefined range. For the DDN, this base case comprises 65 battery-electric AGVs, 160 kWh batteries, 300 kW charging power, 6 chargers evenly distributed along the ASCs and 50% as opportunity charge threshold from where AGVs are allowed to opportunity charge.

Next to this base case, the number of replications and run length are determined; the amount of replications per experiment is determined with the Confidence Interval method, where a precision level of 5% is chosen (Hoad et al., 2007). The run length for the DDN is set at 210,000 time steps, i.e. 146 days, to minimize the influence of the warm-up period.

Sensitivity analysis

A sensitivity analysis is conducted to explore the uncertainty of the model outcomes regarding AGV speed and fuel consumption input. For both these variables, the values are increased and decreased with 25%: AGV speed turns out to have a substantial influence on main terminal KPIs such as ship turnaround times and QC productivity while AGV fuel consumption does not seem to correlate with terminal performance. Therefore, *from a logistical perspective* it is recommended to terminal operators to focus merely on increasing overall AGV speed, e.g. by more efficient routing strategies, rather than making AGVs more energy efficient.

Experiment results

The results of the experiments indicate that the number of AGVs, charging power and number of chargers have a significant effect on the performance of deep sea container terminals. For the DDN, regarding the number of AGVs a convex curve is observed which flattens at 80 AGVs; from this point marginal improvement

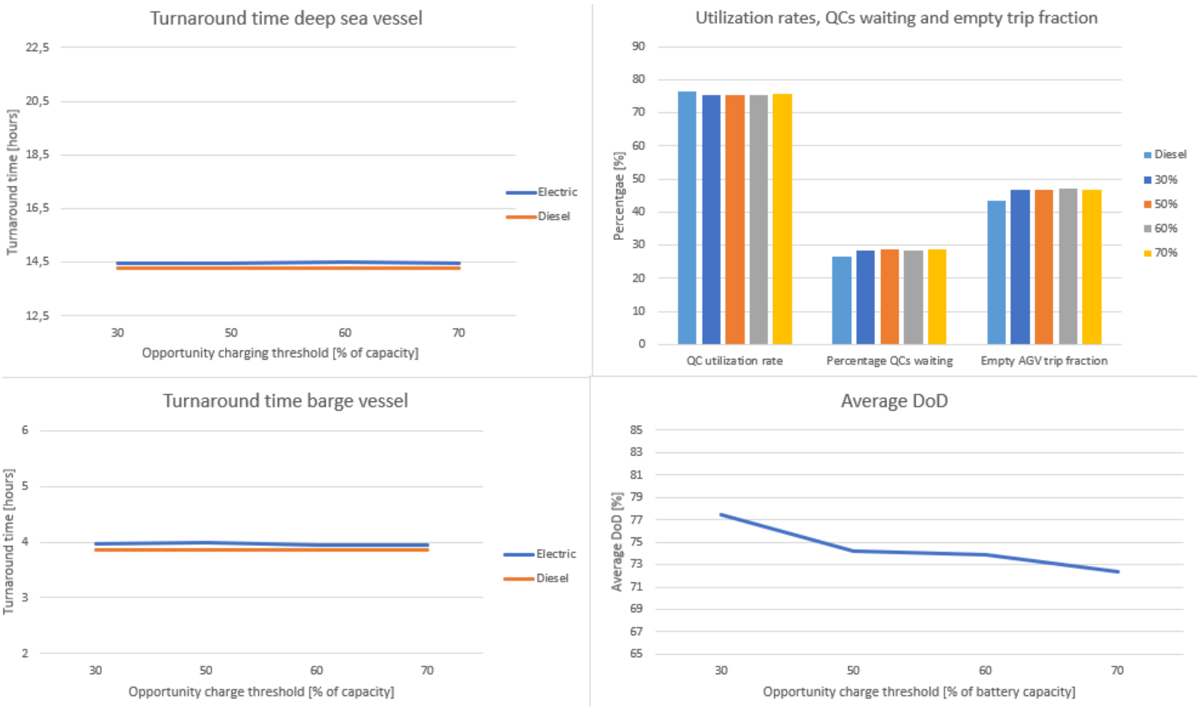


Figure 6.11: Various KPI values for a battery-electric AGV fleet with various opportunity charge thresholds at the DDN; the diesel base case outcomes are included as a current state reference

in turnaround times and terminal productivity is observed. Looking at differences in battery capacities, for the DDN no increase in terminal performance is perceived when increasing the battery size; 60 kWh batteries turn out to perform equally effective as 220 kWh batteries. Apparently, the idle time in between two jobs, 14.84 minutes, is enough to charge the AGV to a sufficient battery level, as is confirmed by the average charging times of 11.09 minutes. Moreover, when looking at the required charging power and number of chargers, 150 kW and 3 chargers prove to be a bare minimum in order to minimize deterioration in terminal performance. When converting these values into the amount of electrical energy charged at a time by an AGV, 35 kWh turns out to be the minimum required charging quantity; acquired from the simulation results that AGVs on average charge once every 5 hours, a charging quantity of 175 kWh is required per day, which approaches the actual daily AGV energy consumption of 140 kWh.

Varying the AGV opportunity charge threshold did not influence the terminal KPIs; a possible explanation could be the fact that AGVs never simultaneously drop to a low battery level due to the battery management strategy implemented and the characteristics of the container transport process.

Evaluating the current and future operational feasibility of charging AGVs

From the experiment results, 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 charging spots turned out to perform operationally equal to the current diesel AGV fleet. It is therefore concluded that the selected AGV charging design, opportunity plug-in charging at the ASC TPs, meets the first design requirement, *Incorporating the AGV charging process into the operational process should lead to equal operational performance compared to the current diesel AGV fleet*, under the condition that a sufficient amount of AGVs, charging power and plug-in chargers are installed. However, until now the current state only has been compared to a future battery-electric AGV fleet, which' implementation is expected within 5 years. Since container throughput is expected to grow within this period, four scenarios have been simulated which incorporate this expected future growth. Subsequently, a 20% and 40% decrease in QC handling time, i.e. 20% and 40% increase in QC capacity, and 20% and 40% increase in ship call sizes, i.e. number of containers to be handled per ship, have been constructed by adjusting the QC handling times and MAIN and BARGE discharge and load sizes respectively. The results indicate that battery-electric AGVs prove to be a robust alternative which are resilient to future growth in terminal throughput; the relative differences in terminal performance (turnaround times,

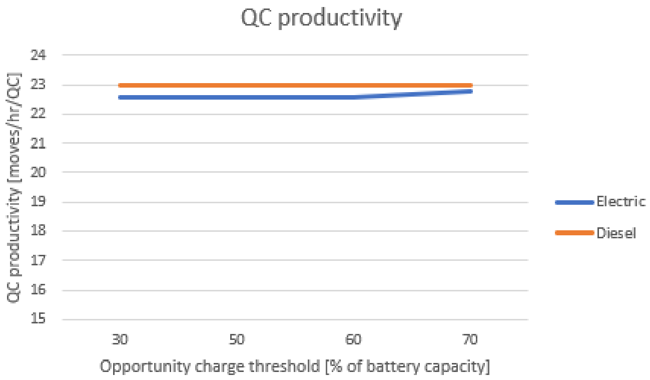


Figure 6.12: QC productivity of a battery-electric AGV fleet with different opportunity charge thresholds at the DDN compared to diesel AGVs

productivity etcetera) remain approximately equal under all described scenarios. Furthermore, the reader is informed that terminal productivity can be increased by either increasing the number of AGVs or by reducing the QC handling times. Increasing the number of AGVs reduces the waiting time of QCs for available AGVs, while reducing the handling time increases a QC's theoretical productivity. From the scenario analysis, it is observed that an increase in QC capacity of 40% leads to 60% higher QC productivity, given the same fleet size. When increasing the fleet size only, however, an increase of 4.5% in QC productivity occurs. Thereby, it is highly recommended to focus on reducing actual QC handling times (e.g. by automating the QC process) rather than improving the AGV-QC interaction in order to be resilient for future growth in container throughput.

Output of this chapter

The main output of this chapter is the answer to the question if replacing diesel AGVs by battery-electric AGVs at brownfield container terminals is an operationally feasible measure. From the experiment results, it is concluded that this is indeed the case under the condition that a sufficient amount of AGVs, charging power and charging spots are available. Moreover, the simulation outcomes regarding MAIN turnaround times will be used as input into the total costs of ownership analysis in the next chapter: turnaround time delays are consequently monetized, reflecting the downtime costs.

7

Total costs of ownership

This chapter aims to answer the last subquestion,
5. To what extent is the AGV charging design financially feasible when compared to diesel AGVs?
by developing a Total Costs of Ownership (TCO) model in which all lifetime costs of an AGV are included. Consequently, this TCO model is applied to the current diesel AGV fleet and a future battery-electric AGV fleet charged according to the selected design, *opportunity plug-in charging at the ASC TPs.* More specifically, by conducting a two stage experiment, in which the design configuration (which number of AGVs, battery capacity, charging power and charging spots?) with the lowest cost difference compared to the current diesel AGV fleet is found in stage 1 whereafter the most promising design configuration from both an operational and financial perspective is tested for a future state with various diesel, electricity and battery price levels in stage 2, the financial feasibility of a battery-electric AGV fleet over a diesel AGV fleet is extensively tested. Started is with the methodology choice for TCO and a general overview of the selected base case and time horizon in section 7.1, after which section 7.2 describes and synthesizes all cost elements that have been incorporated in the cost analysis. Section 7.3 subsequently gives a first insight into the total costs of ownerships of the base cases, whereafter the two stage experimental plan is introduced and the corresponding results are discussed in section 7.4. Section 7.5 presents the results of the performed scenario analysis for diesel, electricity and battery prices in order to give an answer to the question "Is it financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?", whereafter this chapter is ended with a side experiment towards the larger side of the Delta Terminal, the DDE, and a final conclusion. The main methodology used in this chapter is TCO. Figure 7.1 graphically shows the structure of this chapter with the main output and relations between the sections.

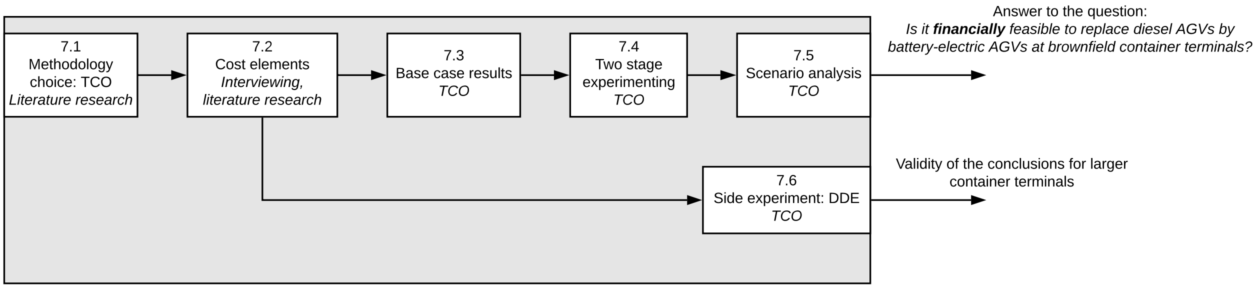


Figure 7.1: Structure, methods and output of Chapter 7

7.1. Methodology choice: total costs of ownership analysis

In this study, a total costs of ownership (TCO) analysis is applied in order to assess a future battery-electric AGV fleet on its economical feasibility. Total costs of ownership as defined by Ellram (1993) considers "total cost of acquisition, use/administration, maintenance and disposal of a given item/service" and is hence valuable to apply in this study; although battery-electric AGVs are more expensive in purchase price, their maintenance and fueling costs are expected to compensate this initial investment (Schmidt et al., 2015). A total costs of ownership uses a predefined base case with which to compare mutually exclusive alternatives over a predefined time horizon. Although main advantage of this method over other methods lies in its comprehensiveness - all cost elements, direct and indirect, over a product's lifetime are considered - its main disadvantage is the fact that the net present value of capital, i.e. the difference in present value of cash inflow and cash outflow over a certain time horizon, is not incorporated in the analysis (Brealey et al., 2012). Hence, including this *time value of cash* will lead to different results; however, while the net present value is merely used for implementation purposes, this study's main objective is to get a first insight into the economic feasibility of replacing diesel AGVs by battery-electric AGVs for which a TCO analysis suffices (Ellram and Siferd, 1998).

7.1.1. Base case

For this study, the base case considered is the current diesel AGV fleet driving at the DDN side of the Delta Terminal in order to compare this fleet's financial performance to a battery-electric AGV fleet, which is the alternative to the base case. The current diesel fleet size is, as earlier mentioned, 65 AGVs.

7.1.2. Time horizon

Next to the definition of the base case, a time horizon within which to evaluate alternatives must be determined. For this determination, the lifetime of the current diesel AGV fleet and its depreciation period is used: 15 years. As battery-electric AGVs are expected to have a longer lifetime - information retrieved from Kalmar's FastCharge AGV reveal a mechanical lifetime of 20 years - the Lithium-Ion batteries of these AGVs are expected to be replaced after 10 years already (Kalmar, 2018). Consequently, the time horizon is set at 15 years in order to make a fair trade-off in longer mechanical life and shorter battery life. However, at the end of this chapter the time horizon is extended to 20 years to investigate how this affects the results.

7.2. Cost elements

As mentioned in section 1.5, the cost elements of Schmidt et al. (2015) as depicted in Figure 1.4 are used as input into the TCO analysis. For every element, a short description as well as main source of information will be given (see Appendix J for the references). However, the reader is attended that in this study an extra cost element is added: downtime costs, which resembles the costs resulting from delays in the transport process, which were shown to be substantial given some AGV charging design configurations (see section 6.3).

7.2.1. Diesel AGVs

For the current diesel AGV fleet, two main components are distinguished: the AGV itself and the corresponding diesel infrastructure in the form of petrol stations. For both components, capital as well as operational expenditures can subsequently be distinguished.

AGV

For the AGV, capital expenditures resemble the initial purchase costs of diesel AGVs including all mechanical and electronic components. ECT experts from the I&E Department state that this purchase price is approximately 500,000 euros. Operating costs are categorized on maintenance and fueling costs. Maintenance costs comprise personnel costs as well as costs made on preventative and corrective maintenance, of which the latter one consists of replacement costs of components during the AGV's lifetime. The total maintenance costs for diesel AGVs are retrieved from experts of the TOD Department. Maintenance costs are divided in a fixed and surplus part: whereas the fixed costs are present in both the maintenance costs for diesel and battery-electric AGVs, the surplus costs are only made for the diesel AGV fleet. For diesel AGVs in particular, the fixed maintenance costs are set at 6 euros per AGV running hour. As AGVs are active 30,000 hours on average over 15 years, the fixed maintenance costs per AGV count up to 180,000 euros. The variable costs cover all components that are not present anymore in battery-electric AGVs, i.e. a diesel engine, ultracapacitor, exhaust system, dynamo, starting engine, radiators and generators. These variable costs count up to, *summed over 15 years*, 103,000 euros per AGV.

Fueling costs are calculated by multiplying the diesel price by the total fuel consumed by all AGVs, which depends on the driving performance, i.e. the fraction of empty trips of the total distance covered; this fraction is preferred to be minimized as empty trips have no added value. The diesel price development over the last four years have been obtained from the Financial Department and is graphically shown in Figure 7.2. Calculated from the original data file, the average diesel price over 2015 was 0,90 euros, over 2016 0,82 euros, over 2017 0,90 euros and over 2018, excluding the last two months as these still have to be determined, 1,00 euros. A clear increase in diesel price can thus be observed. The fuel consumption per kilometer of a diesel AGV has already been calculated in section 3.1.2 and is shown in Figure 3.2: a loaded diesel AGV consumes 7.09 kWh/km while an empty diesel vehicle consumes 4.33 kWh/km.

Regarding driving performance, this will be deducted from the simulation outcomes as the empty trip fraction has also been considered a KPI. Furthermore, the absolute amount of kilometers driven, loaded and empty, has been included in the simulation output and subsequently validated with actual ECT data; the results of this validation are shown in Table 7.1. It can be seen that the simulation model overestimates the amount of kilometers driven by AGVs, which can most likely be explained by the priority rule implemented in the simulation logic: as soon as a QC starts waiting for an available AGV, the priority rule implemented forces AGVs which have become available to drive to this QC, even if the QC-AGV distance is very large. In reality, though, the TOS is able to apply a certain lookahead with which it can be estimated if and when a nearer AGV becomes available for a next job (e.g. within the next minute). Since the percentage of QCs waiting for available AGVs is substantial in the simulation - for the DDN, this percentage is 26.5% of the total QC discharge moves - it is expected that on average more kilometers are covered in the simulation when compared to actual ECT values.

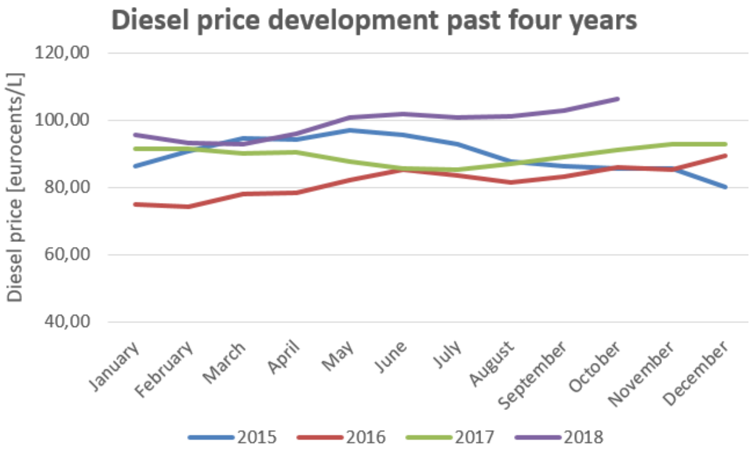


Figure 7.2: Diesel prices paid by ECT over the past four years

Table 7.1: Validation of simulated AGV driving performance with actual ECT values, managing a simulated 43.6% and an actual 44.2% empty AGV trip fraction

	Simulation outcome	**Actual value**	**Matching factor**
Yearly kilometers driven per diesel AGV DDN [km/AGV/year]	12060	10579	86.0%
Of which empty [km/AGV/year]	5258	4676	87.6%
Of which loaded [km/AGV/year]	6802	5903	84.8%

Petrol station

For the diesel infrastructure, the investment costs on new petrol stations are considered as well as the maintenance required on them within the time horizon. Since petrol stations are already present on brownfield container terminals, capital expenditures are excluded for the remainder of this study: ECT experts state that these petrol stations have a very high lifetime which exceed the defined time horizon of 15 years. Maintenance costs are set at 3500 euros per year, in consultation with ECT experts from the TOD Department, circa 3% of the initial investment costs.

7.2.2. Battery-electric AGVs

For battery-electric AGVs, a third cost component is considered next to the AGV and the corresponding charging infrastructure: the battery, which' lifetime is shorter than the defined time horizon and thus has to be replaced within 15 years. Also, downtime costs are incorporated as these comprise the delays *relative to the base case*, i.e. diesel AGVs.

AGV

Regarding the AGV, similar cost components are distinguished as for a diesel AGV fleet. The purchase price of a battery-electric AGV **excluding the battery costs** is similar to its diesel counterpart: 500,000 euros. Expected is that the fueling costs will decrease due to a higher energy efficiency of battery-electric AGVs and a lower electricity kWh price when compared to the diesel price per liter; the kWh price ECT currently pays is 0.07 €/kWh and has been consequently used as default price (Eurostat, 2018). However, as was concluded from Chapter 6, the empty AGV trip fraction increases with the introduction of battery-electric AGVs, which thus could hamper this increase in energy efficiency and cost effectiveness. Considering the DDN base case of a fully battery-electric AGV fleet, the expected empty and loaded kilometers driven per AGV per year have been obtained from the simulation outcomes; the results are presented in Table 7.2. It is shown that with the introduction of a battery-electric AGV fleet, the total distance covered per AGV increases with about 4.1% due to more frequent empty charging trips to the ASCs when compared with diesel AGV tanking.

Next to fueling costs, battery-electric AGVs are also expected to be less maintenance sensitive when compared to their diesel counterpart: main reason lies in the reduced amount of moving parts and the absence of the diesel engine, which takes up a large share in the current daily AGV maintenance (around 30%). While battery-electric AGVs are expected to save 103,000 euros on maintenance costs per AGV (see section 7.2.1), this is almost fully compensated with the battery replacement costs as Li-Ion batteries currently on the market have a lifetime of approximately 10 years (Kalmar, 2018; VDL, 2018a). Over a 15 years time horizon, the relative savings in maintenance costs per AGV will thus equal 103,000 - (160 kWh x 600 euros/kWh) = 7,000 euros per AGV.

To conclude, while battery-electric AGVs are more expensive in purchase price, it is expected that their lower operational expenditures will compensate these higher initial investments.

Table 7.2: Comparison of the annual kilometers driven of a fully battery-electric AGV fleet and a diesel AGV fleet for the DDN

	Battery-electric AGV fleet	**Diesel AGV fleet**	**Relative increase**
Yearly kilometers driven per AGV DDN [km/AGV/year]	12549	12060	4.1%
Of which empty [km/AGV/year]	5885	5258	11.9%
Of which loaded [km/AGV/year]	6664	6802	-2.0%

Charging infrastructure

While Schmidt et al. (2015) used battery swapping stations as physical charging technique, this study's selected design alternative of the AGV charging process, opportunity plug-in charging at the ASC TPs, makes use of plug-in charging as depicted in Figures E.1 and E.2; the 10 foot container supplies the required power to the plug-in charger which, on its turn, makes connection with the AGV. A distinction is made between building costs and maintenance costs. In consultation with Heliox and ECT experts, the most important building cost elements are cabling costs, energy transformer costs and the purchase costs of the plug-in chargers. Cabling costs are caused by connecting the 10 foot charge energy supplier with the smaller plug-in charger and the electricity grid; energy transformer costs depend on the charging power that is required and consequently must be distributed through the electricity grid to the 10 foot charge supplier. Experts from the I&E Department have roughly calculated the building costs of the DDN base case configuration with 6 chargers installed along stack side with a charging power of 300 kW. The corresponding cost estimate equals 1,750,000 euros, excluding the purchase costs of a charger. From section 3.3.1 and Table 3.4, it is retrieved that these purchase costs equal 200,000 euros per charger.

Finally, the expected annual maintenance costs are expressed as a percentage of the initial investment costs. In consultation with experts from quick charge supplier Heliox, this percentage is set at 3%.

Battery

Since this study considers Lithium-Ion batteries only, the purchase and maintenance costs of this battery type have been used accordingly as input into the TCO analysis. Lithium-Ion batteries have high capital expenditures while they are almost maintenance free throughout their lifetime (Khaligh and Li, 2010; VDL, 2018a). Regarding the purchase costs, Lithium-Ion costs 500-1000 euros per kWh capacity, as obtained from Table 3.3. In consultation with VDL, manufacturer of battery-electric AGVs, a kWh price of 600 euros has been used. However, it should be noted that this kWh price is most likely to drop within the near future if battery use become more widespread in the private vehicle industry (Gaines and Cuenca, 2000).

Downtime costs

Downtime costs are expected to take up a significant share in the total costs of ownership of a fully battery-electric AGV fleet. As was shown in Chapter 6, the deterioration in terminal performance can be quite substantial for particular design configurations. For terminal operators, downtime costs can be operationalized in several ways, of which the most common way is monetizing the delay in turnaround times of deep sea vessels, i.e. MAINS (Lang and Veenstra, 2010; Pachakis and Kiremidjian, 2004; Rodriguez-Alvarez et al., 2011). ECT also applies this method in measuring port downtime costs. Generally, three factors can be distinguished in monetizing delays in MAIN turnaround times:

1. Extra labor costs for crane operators; at ECT, three operators are simultaneously active per crane for whom 60 euros are paid per extra man-hour.

2. Missed incomes on handling containers due to vessel delays. If a vessel has a delay of 30 minutes, no consecutive ship can be handled within this half an hour. Consequently, QCs remain idle for a longer amount of time which can be monetized by multiplying the value of handling one container by the QC productivity and the amount of QCs per MAIN ship. At ECT, the value of one handled container equals approximately 100 euros. It must be noted that this calculation resembles the most pessimistic scenario: in practice, it is not often observed that large vessels arrive one after another, thus including all missed incomes on handling containers of a consecutive ship might not be valid. However, since these true delay costs are hard to estimate, it is assumed that all delays in turnaround times of MAINS result in missed incomes (theoretical loss of terminal productivity).

3. Penalties claimed by the shipping company due to delays. According to ECT experts from the Logistical Department, this factor can take up a significant share in the total downtime costs. However, as the ECT Financial Department were reluctant to share these penalty values per hour delay, this has been left out of the TCO analysis.

7.2.3. Additional costs

Not included in the cost element model of Schmidt et al. (2015) are the *pilot* costs for developing a battery-electric AGV prototype, *implementation* costs regarding retraining maintenance employees, adjusting maintenance stations and developing a new battery management communication system between AGVs and the TOS and *disposal* costs of AGVs and their components after their lifetime. Pilot costs for the battery-electric AGV are estimated to equal once 50,000 euros. Initial implementation costs will fluctuate around 190,000 euros, of which 50,000 euros for adjusting maintenance work stations, 40,000 euros for retraining the maintenance crew and 100,000 euros for the development of a battery management communication system. Disposal costs of diesel AGVs and their components are negligible as they do not contain chemical materials; for Lithium-Ion battery-electric AGVs, disposal costs are estimated to equal 4,000 euros per ton Lithium-ion battery (Battery University, 2018f). For the default 160 kWh batteries weighing 4 tons used in this study as the base case, consequently 4x4,000 = 16,000 euros must be paid for recycling one battery.

Next to costs, several incomes are to be expected when investing in a fully battery-electric AGV fleet. According to section 4.3.1, on average 13.5% of the initial investments made on zero-emission AGVs can be saved when opting for the EIA subsidy. Also, 30% of the pilot and implementation costs can be saved when making use of the WBSO regulation. Finally, an AGV's salvage value, excluding the battery, is, according to ECT experts from the I&E Department, approximately 5,000 euros, both for the diesel and battery-electric variant. The salvage value of a Lithium-Ion battery equals, using a dollar-to-euro conversion factor of 0.8789, approximately 950 euros per ton (Rockaway Recycling, 2018). For the default 160 kWh batteries weighing 4 tons, the salvage value consequently equals 3,800 euros per battery.

7.2.4. Synthesis of cost elements

All cost elements retrieved and discussed in this section for both the diesel and battery-electric variant are synthesized in Table 7.3. The costs of one hour delay in MAIN turnaround time have been calculated as follows: 3 crane operators per QC multiplied with the amount of QCs handling one MAIN ship plus 100 euros per missed container multiplied with the average QC productivity and the number of QCs handling one MAIN. Consequently, one hour delay **at the DDN** equals (3x60x4)+(100x22x4)= 9,520 euros extra costs, given that 4 QCs are on average handling one MAIN ship.

Regarding the charging infrastructure costs, 1,750,000 euros is the cost estimate for the default configuration of the DDN, i.e. 6 chargers distributed evenly along the stacks at 300 kW charging power. For the remainder of the TCO analysis, it is assumed that in case twice as much chargers are installed the underlying infrastructure costs will also double. Also, in case the charging output power doubles (from 300 kW to 600 kW) the total infrastructure costs are doubled. It must be noted that this assumption is not valid since charging output power is not linearly related to infrastructure costs, so is the number of chargers (it depends on the installment of a new transformer house or connection to an existing one, which can only be judged by ECT experts). However, rather than letting experts estimate the infrastructure costs of all the experiment variants, this alternative method has been applied which is indeed a limitation of the performed TCO analysis.

Finally, the reader is noted that almost all cost elements shown in Table 7.3 are obtained from experts from ECT, quick charger supplier Heliox and AGV manufacturers VDL and Kalmar since there is a lack of literature on costs of battery-electric AGVs at container terminals; see Appendix J for the expert references.

Table 7.3: Overview of the cost elements obtained from experts of ECT, Heliox, VDL and online sources

	Value	Obtained from
Capital expenditure elements		
Pilot costs [€]	50,000	I&E
AGV purchase costs [€/AGV]	500,000	I&E
Battery costs per kWh Li-Ion [€/kWh]	600	VDL
Quick charger purchase costs [€/charger]	200,000	Heliox, Kalmar
Charging infrastructure costs [€]	1,750,000	I&E
Implementation costs [€]	190,000	I&E, LD
Operational expenditure elements		
Price per kWh energy [€/kWh]	0,07	I&E, (Eurostat, 2018)
Price per liter diesel [€/L]	1,00	I&E
Fixed maintenance costs per AGV running hour [€/hour/AGV]	6	TOD
Surplus maintenance costs diesel AGV [€/AGV]	103,000	TOD
Annual quick charger maintenance costs [% of purchase price]	3	Heliox
Annual petrol station maintenance costs [€/year]	3,000	TOD
Delay costs per hour TAT MAIN [€/hour]	9,520	LD
Disposal costs Li-Ion battery [€/battery]	16,000	(Battery University, 2018f)
Income elements		
EIA subsidy [% of initial vehicle costs]	13.5	(RVO, 2018a)
WBSO subsidy [% of initial prototype and retraining costs]	30	(RVO, 2018b)
Salvage value AGV [€/AGV]	5,000	I&E
Salvage value Li-Ion battery [€/battery]	3,800	(Rockaway Recycling, 2018)

7.3. Base case results

For the economical evaluation of opportunity plug-in charging battery-electric AGVs at the ASC TPs, experiments have been conducted for the DDN. First, the total costs of ownership for the diesel and battery-electric base case, for which the default variable values are depicted in Table 6.1, have been calculated. The outcomes are presented in Table 7.4; the calculations made for obtaining the resulting values are described and explained in Appendix H. From the results, it is seen that the battery-electric AGV base case does not outperform its diesel counterpart for the DDN. This is mainly caused by the very high downtime costs compared to the current situation with diesel AGVs. While electric AGVs prove to be more energy efficient - fueling costs halve when deploying this type of AGVs even though the total distance covered per AGV increases - this gain cannot compensate the increase in initial investments and the resulting downtime costs. What can thus be concluded is that reducing downtime costs will lead to a substantially more beneficial TCO for the battery-electric AGV variant, which implies that this is at the expense of (much) higher initial investment costs. When excluding downtime costs, it is observed that the ratio capital expenditures:operational expenditures is approximately 2:1 for the battery-electric AGV fleet and 1:1 for diesel AGVs. It is thus proven that electric AGVs are more cost effective throughout their lifetime with regard to the initial investments when compared to diesel AGVs, for which around the same operational expenditures as capital expenditures are paid. Including the incomes leads to an even more cost effective battery-electric AGV solution. Though, downtime costs must be incorporated as this is the core business of a terminal operator.

Table 7.4: Total costs of ownership for the diesel and battery-electric AGV base case over 15 years in euros

	Diesel base case	**Battery-electric base case**
Capital expenditures		
Pilot costs	-	50,000
AGV purchase costs (including battery)	32,500,000	38,740,000
Charging infrastructure costs	-	3,050,000
Implementation costs	-	90,000
Total	**32,500,000**	**41,930,000**
Operational expenditures		
Fueling costs	17,659,250	4,984,993
AGV maintenance costs	18,392,400	17,940,000
Infrastructure maintenance costs	45,000	540,000
Downtime costs	-	19,635,000
Disposal costs	-	1,040,000
Total	**36,096,650**	**44,118,719**
Incomes		
EIA subsidy	-	5,229,900
WBSO subsidy	-	27,000
Salvage incomes AGV	325,000	325,000
Salvage incomes battery	-	247,000
Total	**325,000**	**5,828,900**
Total costs of ownership	**68,271,650**	**80,241,094**

7.4. Two stage experimenting

Instead of considering the base case only with a fixed design configuration, chosen is to perform a two stage filtering or experimenting procedure for the battery-electric AGV fleet only. The current diesel AGV fleet is chosen to be the reference case which does not vary throughout the experiments as this reflects the current state at the Delta Terminal:

1. in the first stage, a similar experimental analysis as performed in Chapter 6 using the experimental plan depicted in Table 6.1 is conducted. As was concluded from Chapter 6, the opportunity charge threshold value, from which an AGV is allowed to opportunity charge its battery, did not have an influence on terminal performance. Since varying this value does not 'cost extra' - an AGV that is allowed to start charging at 70% does not differ from using a 30% threshold - this variable has been left out of the experiments. The other variables, however, showed to influence terminal performance - or are believed to influence terminal operator's finance - and are therefore varied over the ranges defined in Table 6.1.

2. in the second stage, the most promising design configuration from both an operational and financial perspective, considering *number of AGVs*, *battery capacity*, *charging power* and *number of charging spots*, that has been obtained from the first stage experiments and from Chapter 6 are used for comparison with the current diesel AGV fleet by performing a sensitivity analysis on the diesel, electricity and Lithium-Ion battery price in order to investigate if and under what conditions a battery-electric AGV fleet becomes financially feasible compared to a diesel AGV fleet.

7.4.1. First stage experiment results

This section presents the results of the conducted experimental analysis for first stage comparison. According to the calculations performed for the DDN base case, which are described in Appendix H, the TCOs of all experiments have been obtained. Most important to mention are the cost elements that are influenced by each experiment; these are shown in Table 7.5. Fueling and downtime costs seem to be influenced by all variables. Fueling costs change dependent on the empty AGV trip fraction and the amount of kilometers driven per AGV, which are obtained per experiment from the simulation outcomes. For example, installing more chargers evenly along the ASCs reduces the total distance covered by AGVs, and consequently also lowers the empty AGV trip fraction, as the average distance to a charger becomes smaller. Downtime costs are also obtained from the simulation outcomes where the difference in MAIN turnaround time of the battery-electric variant and diesel base case is considered the delay in minutes. Finally, the reader is reminded that it is assumed that in case twice as much charging power or chargers are needed, the charging infrastructure costs double.

By varying all four variables, the graphs in Figure 7.3 are obtained. What immediately can be observed are the similarities in shape with the simulation experiment results discussed in Chapter 6 and depicted in Figures 6.3, 6.5, 6.7 and 6.9. This is due to the fact that downtime costs take up a significant share in the total costs of ownership. A final note must be made on the word 'optimal': the minima obtained from Figure 7.3 are optimal given the other variables that have been fixed. For example, 75 battery-electric AGVs turn out to result in the lowest cost difference with diesel AGVs given that the base case, 160 kWh batteries, 300 kW charging power and 6 chargers, is applied. As a consequence, varying the other variables as well could lead to different optima, which is indeed a limitation of this study. However, for finding an operationally and financially *feasible* instead of optimal configuration, the applied method is expected to suffice.

Table 7.5: Variables to be varied and their influence on cost elements

	Changes the cost elements:
Number of AGVs	AGV purchase costs, fueling costs, AGV maintenance costs, downtime costs, disposal costs, incomes
Battery capacity	AGV purchase costs, fueling costs, AGV maintenance costs, downtime costs, disposal costs, incomes
Charging power	Charging infrastructure costs, fueling costs, downtime costs, incomes
Number of chargers	Charging infrastructure costs, fueling costs, infrastructure maintenance costs, downtime costs, incomes
DDN	Pilot costs

Number of AGVs

Whereas Figure 6.3 indicates that 95 AGVs are better than 75 from an operational perspective, the TCO results find an optimum at 75 AGVs. As 75 AGVs already avoid downtime for large vessels and thus result in zero downtime costs, a further increase unnecessarily leads to higher initial investment costs and is therefore suboptimal. Extending the current fleet driving at the DDN with 10 AGVs thus leads to a more favorable TCO *given the base case design configuration of 160 kWh batteries, 300 kW charging power and 6 chargers divided along the stacks.*

Battery capacity

Similar to Figure 6.5, Figure 7.3 shows that varying battery capacities do not influence the total costs of ownership. This is because of the equal downtime costs (circa 10-15 minutes delay in MAIN turnaround times); yet, while slight gains in MAIN turnaround times are made when increasing the capacity to 160 kWh, no increase in performance is made when extending the capacity further after this value. From this point, an increase in TCO is observed. As a result, 160 kWh batteries turn out to be the most cost efficient solution *given the base case design configuration of 65 AGVs, 300 kW charging power and 6 chargers.* This is in accordance with industry key players' choices.

Charging power

Regarding charging output power, it can be seen that improvement in TCO is made until 600 kW. This is in accordance with Figure 6.7 where operational performance increases with higher output powers. Apparently, higher infrastructure costs do not heavily influence the total costs of ownership, which is confirmed when looking at Table 7.4: initial charging infrastructure costs are approximately 3-4% of the battery-electric base case TCO. It is thus concluded that 600 kW charging power is the most cost effective solution for the DDN *given the base case design configuration of 65 battery-electric AGVs, 160 kWh batteries and 6 chargers.*

Number of chargers

By varying the number of chargers it was found that 6 chargers result in the lowest cost difference when compared to the diesel base case, which is in accordance with Figure 6.9. Purchasing and installing more than 6 chargers unnecessarily adds to the total costs of ownership *given the base case design configuration of 65 AGVs, 160 kWh batteries and 300 kW charging power.*

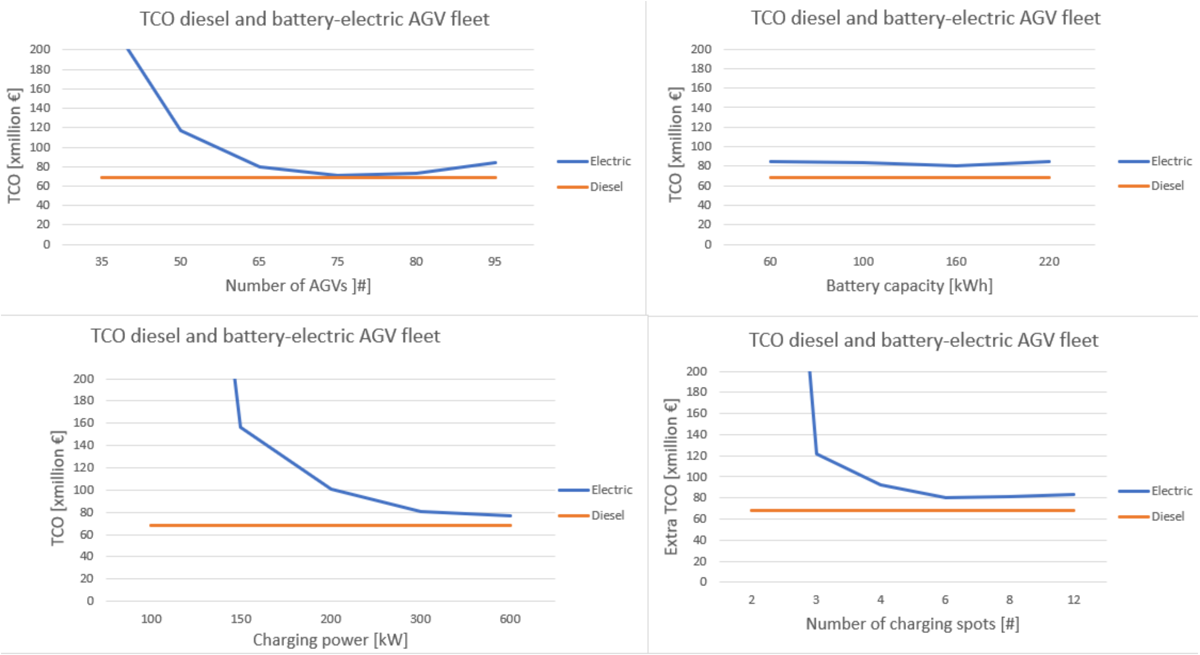


Figure 7.3: Total costs of ownership of both a diesel and battery-electric AGV fleet for the DDN

Operationally and financially most promising design configuration

In Table 7.6, the cost difference of the design variables varied within the first stage experimental plan when compared to diesel AGVs is depicted. As can be seen, the base case design configuration where the number of AGVs has increased from 65 to 75 AGVs results in the lowest cost difference with diesel AGVs and is thus most promising to be implemented from a financial perspective. However, there must also be accounted for the design configuration that has been evaluated on its operational feasibility; from section 6.4, it is recalled that this design configuration is similar to the configuration that is selected from Table 7.6 from a financial perspective. This can most likely be explained by the absence of downtime costs in this configuration, while for the other configurations (slight) downtime costs still occur. Apparently, reducing downtime costs to zero outweighs the higher initial investment costs in vehicles and batteries. As the configuration with **75 AGVs, 160 kWh batteries, 300 kW charging power and 6 charging spots** is both operationally and financially promising to be implemented, this configuration has subsequently been selected for further evaluation on its financial performance by means of a sensitivity analysis in the remainder of this chapter.

7.4.2. Second stage experiment results

Table 7.7 presents the TCO of the above selected design configuration with the current price levels; it can be seen that no downtime costs occur with this setting. However, diesel AGVs still remain financially favorable over a fully battery-electric AGV fleet due to their lower initial investment costs.

7.5. Scenario analysis

Assuming that several input values into the TCO analysis remain fixed over 15 years is most likely invalid. For example, when looking at the diesel purchase price development in Figure 7.2 it can be seen that diesel prices on average have increased from 0,90 euros in 2015 to 1,00 euros in 2018. Excluding the months November and

Table 7.6: First stage experiment results

Design variable	Value	Cost difference with diesel AGVs [€]	Selected configuration
Number of AGVs [#]	35	173,514,290	
	50	48,965,656	
	65	11,948,169	
	75	1,940,822	x
	80	6,504,329	
	95	16,067,153	
Battery capacity [kWh]	60	16,286,341	
	100	15,069,719	
	160	11,948,169	
	220	16,192,608	
Charging power [kW]	100	765,830,763	
	150	87,806,654	
	200	32,810,045	
	300	11,948,169	
	600	8,258,579	
Number of chargers [#]	2	790,390,825	
	3	53,768,448	
	4	23,790,654	
	6	11,948,169	
	8	13,052,566	
	12	15,344,312	

December of 2018 as these have not been determined yet, a rising trend in diesel price is observed. However, it must be noted that this increase could also be caused by temporary disruptions since the development of diesel prices over the past years frequently has shown this increase-decrease interplay visualized in Figure 7.4. The kWh price, on the contrary, shows a more stable price development as shown in Figure 7.5. Although this is an EU overall average, it is checked whether this development holds for the Netherlands in particular: data from CBS (2018) show a similar development in electricity prices over the last 10 years.

With regard to the future, both the diesel and electricity price developments are uncertain as these depend on several external factors. If the deployment of electric vehicles for private and industry use becomes more widespread, economies of scale could lower the kWh price while an increase is expected due to a potential overload of the electricity grid with certain electricity consumption patterns. More specifically, if terminal (and AGV) peak hours would frequently overlap with the electricity market's peak hours, this will result in higher kWh prices. Schmidt et al. (2014) conducted research on this topic by assessing the economic viability of shifting charging of battery-electric AGVs to electricity market's off-peak hours. They found that almost 65% operational cost savings can be achieved when applying off-peak charging in combination with feeding electricity back to the power grid. Although assessing these strategies is outside the scope of this study, it is interesting to investigate both an increase and decrease in kWh prices.

Regarding the diesel price, it is expected that this will increase in the (near) future as ECT data already shows an increase from 2015 onwards. Going back further, the diesel price ECT paid in 2009 was approximately 0.60 euros (Teuwen, 2009). When extrapolating this trend, a diesel price of 1.50 euros per liter can be expected over 15 years, assuming an increase of 0.10 euros per 3 years. The rise in diesel prices is confirmed by the current trend in government policies towards sustainable energy use.

Finally, the price per kWh of Lithium-Ion batteries will most likely decrease in the near future due to economies of scale if electric vehicles become more widespread (Blomgren, 2017). An indication in future price cannot be given as this will depend on various external factors, such as future availability of lithium as a scarce resource and geopolitical dynamics.

7.5.1. Scenario construction

Before experimenting with various input values, the design configuration that was regarded most promising for the DDN from an operational and financial perspective, 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 chargers installed evenly along the ASCs, is selected. Consequently, the scenario analysis as depicted in Figure 7.6 has been constructed and applied to this alternative. Chosen is for a Lithium-Ion price level that remains either constant or drops to 400 €/kWh as it is uncertain whether and to what extent the purchase prices will eventually drop. For the electricity price, also the current price level has been maintained and a price level which has almost halved. This is decided upon as it remains uncertain whether the electricity grid is resilient for substantial increases in energy demand. In case it is, in accordance with the decreasing

Table 7.7: Total costs of ownership of the most promising design configuration for the DDN

	[75 AGVs, 160 kWh batteries, 300 kW charging power, 6 chargers]
Capital expenditures	
Pilot costs	50,000
AGV purchase costs (including battery)	44,700,000
Charging infrastructure costs	4,800,000
Implementation costs	90,000
Total	**49,640,000**
Operational expenditures	
Fueling costs	4,853,971
AGV maintenance costs	20,700,000
Charger maintenance costs	540,000
Downtime costs	-
Disposal costs	1,200,000
Total	**27,293,971**
Incomes	
EIA subsidy	6,034,500
WBSO subsidy	27,000
Salvage incomes AGV	375,000
Salvage incomes battery	285,000
Total	**6,721,500**
Total costs of ownership	**70,212,471**
TCO difference with diesel AGVs	**1,940,822**

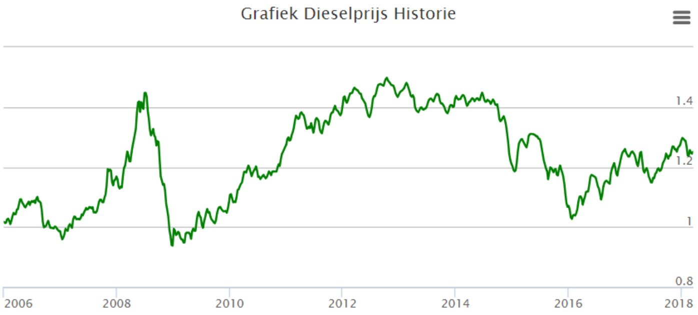


Figure 7.4: Development of consumer diesel prices per liter in the Netherlands from 2008 until 2018 (Dieselprijs, 2018)

trend shown in Figure 7.5 kWh prices will most likely drop. Finally, diesel prices are most likely expected to rise further as ECT data shows a continuous increase in the price per liter over the past years. Therefore, it is decided to define a conservative estimate (1.25 €/L) and a pessimistic scenario (50% increase in diesel price).

7.5.2. Scenario results

Figures 7.7 and 7.8 show the outcomes of the performed scenario analyses. A bar which is larger than zero resembles a higher TCO of the battery-electric AGV fleet compared to its diesel counterpart, a negative bar reflects a lower TCO. It is perceived that under all defined scenarios a battery-electric AGV fleet becomes financially feasible and viable over diesel AGVs. This is especially due to the increase in diesel price, which can be explained by Table 7.4: whereas almost no improvement in AGV maintenance costs is made when shifting from diesel to battery-electric AGVs, on the contrary a substantial decrease in fueling costs is observed. For the DDN diesel base case, fueling costs comprise 26% of the total costs of ownership, while battery-electric AGVs' fueling costs are only 6% of the TCO. With this in mind, it can easily be reasoned that especially the diesel price is a decisive factor in determining the financial feasibility of battery-electric AGVs when compared to diesel AGVs rather than the electricity price: slight increases in diesel prices substantially influence the TCO of diesel AGVs and thus the cost difference with electric vehicles. The Li-Ion battery price appears not be a crucial factor for the financial feasibility as even with current Li-Ion price levels battery-electric AGVs prove to be financially feasible and viable over diesel AGVs. Hence, overall it can be concluded that, assuming that the current trend in diesel and electricity prices will continue in the (near) future, battery-electric AGVs prove to be a more cost-effective alternative than their diesel counterpart.

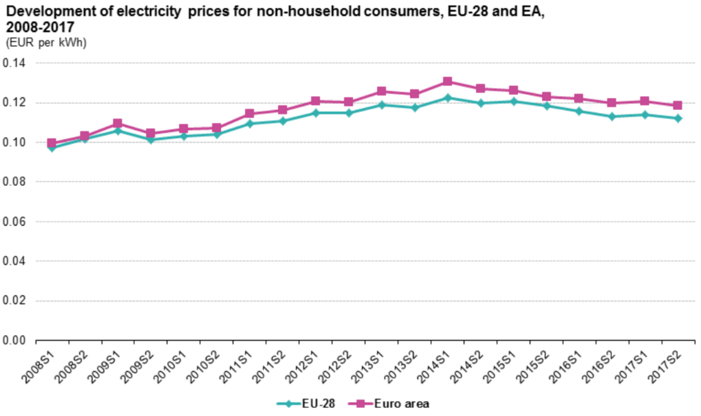


Figure 7.5: Development of electricity prices per kWh in the European Union; Netherlands' price lies under the overall average (Eurostat, 2018)

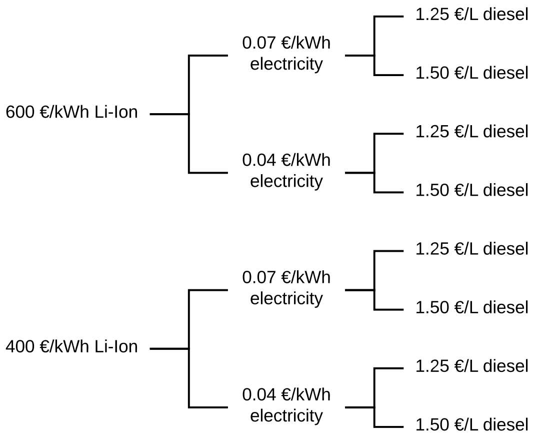


Figure 7.6: Scenario variants to be evaluated for both the DDN and DDE

7.5.3. Extension of time horizon: sensitivity in time

As mentioned at the beginning of this chapter, a time horizon of 15 years is chosen as default when considering the lifetimes of diesel AGVs, Li-Ion batteries and battery-electric AGVs; Schmidt et al. (2014) and Schmidt et al. (2015) also used 15 years to compare a diesel and battery-electric AGV fleet. However, since battery-electric AGVs have a mechanical lifetime of 20 years, the time horizon has consequently been extended to 20 years. As diesel AGVs most likely must be replaced within this time frame, it was checked whether the TCO of the operationally and financially most promising design for the DDN is favorable when taking this extra purchase of 65 diesel AGVs into account: observed was that, using the default price elements summarized in Table 7.3, the TCO indeed became favorable relative to the diesel base case (-50 million euros). Since this was in line with expectation, more interesting to investigate is to what extent the TCO becomes beneficial given a lifetime of 20 years for both types. Consequently, the time horizon is extended to 20 years while the number of diesel AGVs to be purchased remained fixed at 65 AGVs. For all scenarios constructed in Figure 7.6 the extra TCO of battery-electric AGVs relative to diesel vehicles have been calculated. The results are shown in Figures 7.9 and 7.10; it was perceived that for the DDN the total costs of ownership now also become favorable with the current price levels (0.07 €/kWh, 1.00 €/L diesel and €600/kWh battery capacity). This is explained by the rising pressure of fueling costs on the total costs of ownership of the diesel variant, given that battery-electric AGVs become beneficial in scenarios with higher diesel prices. For the most pessimistic diesel price scenario and most optimistic electricity price scenario, this cost difference with diesel AGVs even counts up to 19 million euros, which means that battery-electric AGVs in potential have a strong financial performance when compared to the current diesel AGV fleet.

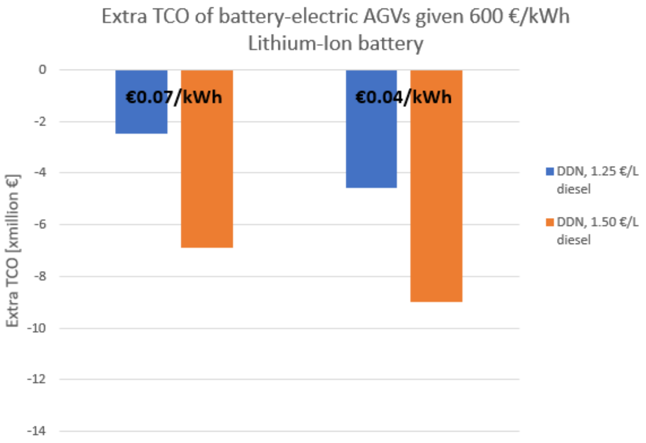


Figure 7.7: Extra total costs of ownership of a battery-electric AGV fleet compared to the diesel base case under a fixed 600 €/kWh Li-Ion battery price and variable diesel and electricity prices

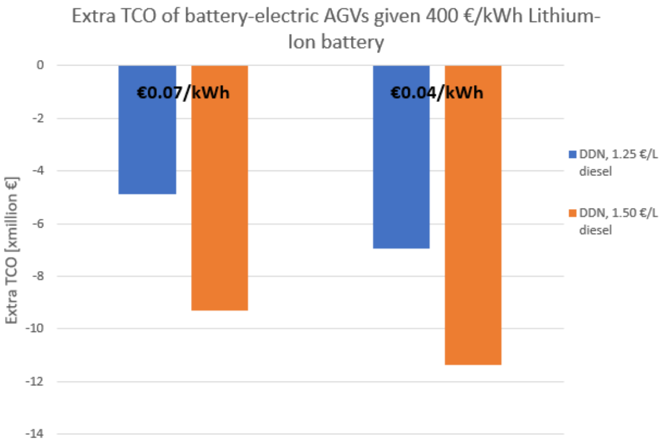


Figure 7.8: Extra total costs of ownership of a battery-electric AGV fleet compared to the diesel base case under a cheaper 400 €/kWh Li-Ion battery price and variable diesel and electricity prices

7.6. Side experiment: the DDE

While this study's main design and research scope comprises the DDN side of the Delta Terminal, as a side experiment the financial feasibility on the larger side of the Delta Terminal, the DDE, has been evaluated as well. Appendix I elaborates upon this extensively; here, it suffices to mention that battery-electric AGVs prove to be especially financially viable at larger container terminals due to the substantial reduction in fueling costs, which seem to heavily outweigh the higher initial investment costs in electric vehicles and charging infrastructure.

7.7. Conclusion

This chapter elaborated upon the total costs of ownership (TCO) of a battery-electric AGV fleet charged according to the selected design of Chapter 4 compared to a diesel AGV fleet in order to answer the last subquestion:
5. To what extent is the AGV charging design financially feasible when compared to diesel AGVs?

To answer this subquestion, the cost elements of Schmidt et al. (2015), which are visualized in Figure 1.4, have been used. Additionally, downtime costs, for which the delays in deep sea vessel (MAIN) turnaround times have been monetized, and salvage incomes from AGVs and batteries are included to complete the list of costs. Using a time horizon of 15 years, a fully battery-electric AGV fleet has been compared to a diesel

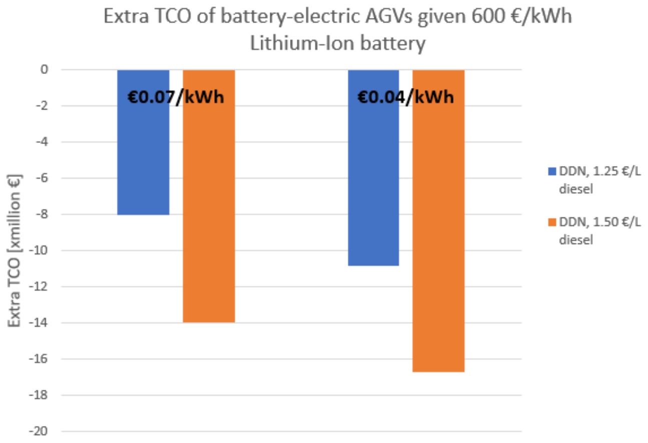


Figure 7.9: Extra total costs of ownership of a battery-electric AGV fleet over a 20 years time horizon with a fixed 600 €/kWh Li-Ion battery price

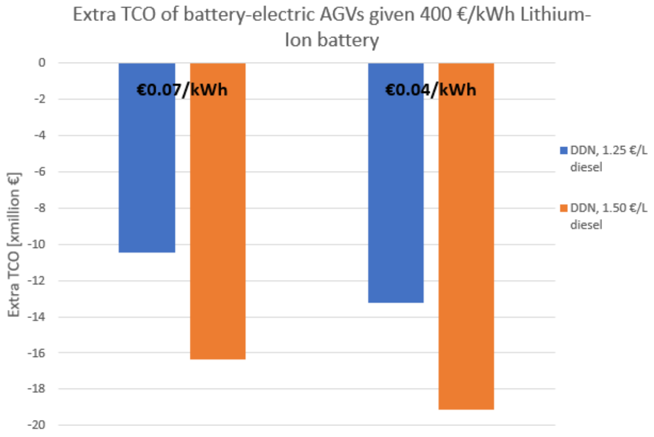


Figure 7.10: Extra total costs of ownership of a battery-electric AGV fleet over a 20 years time horizon with a cheaper 400 €/kWh Li-Ion battery price

AGV fleet. The base case as defined for the simulation experiments for the DDN in Table 6.1 has been used to gain a first insight into the financial feasibility of a battery-electric AGV fleet over a diesel AGV fleet. The total costs of ownership count up to 80,241,094 euros over 15 years of which downtime costs cover almost 25% of the TCO; a fully diesel AGV fleet at the DDN costs approximately 68,271,650 euros. Unknown, though, is what combination of design variables, i.e. number of AGVs, battery capacity, charging power and number of chargers, result in the lowest cost difference with diesel AGVs. Therefore, a two stage experimental analysis has been conducted: in the first stage, similar experiments as with the experimental plan of Chapter 6 have been performed. The second stage subsequently looked for the design configuration with the lowest total costs whilst ensuring operational feasibility. For the DDN, the configuration that turned out to be most cost effective comprises 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 chargers installed evenly along the ASC TPs; the extra lifetime costs compared to a diesel AGV fleet are equal to 1,940,822 euros. Consequently, this configuration has been evaluated further on its sensitivity to changes in diesel, electricity and Lithium-Ion battery prices, cost parameters which are likely to vary in the (near) future.
From this scenario analysis, it was observed that especially future increases in diesel price result in a positive TCO for battery-electric AGVs. This is explained by the fact that, unlike AGV maintenance costs, improvement in operational expenditures is mostly made by the reduction in fueling costs, which cause around 25% of the total costs of ownership of diesel AGVs while only 6% of the battery-electric AGVs' lifetime costs. With this in mind, it can easily be reasoned that especially the diesel price is a decisive factor in determining the financial feasibility of battery-electric AGVs when compared to diesel AGVs rather than the electricity price:

slight increases in diesel prices substantially influence the TCO of diesel AGVs and thus the cost difference with electric vehicles. The Li-Ion battery price appears not be a crucial factor for the financial feasibility as even with current Li-Ion price levels battery-electric AGVs prove to be financially feasible and viable over diesel AGVs. Hence, overall it can be concluded that, assuming that the current trend in diesel and electricity prices will continue in the (near) future, battery-electric AGVs prove to be a more cost-effective alternative than their diesel counterpart.

When extending the time horizon to the mechanical lifetime of battery-electric AGVs, 20 years, it is perceived that for the DDN the total costs of ownership now also become favorable with the current diesel, electricity and battery price levels. This is explained by the rising pressure of fueling costs on the total costs of ownership of the diesel variant, given that battery-electric AGVs become beneficial in scenarios with higher diesel prices. For the most pessimistic diesel price scenario and most optimistic electricity price scenario, this cost difference with diesel AGVs even counts up to 19 million euros, which means that battery-electric AGVs in potential have a strong financial performance when compared to the current diesel AGV fleet. From the side experiment conducted for the DDE side of the Delta Terminal, it can be concluded that a battery-electric AGV fleet proves to be especially financially viable at larger container terminals due to the substantial reduction in fueling costs, which seem to heavily outweigh the higher initial investment costs in electric vehicles and charging infrastructure.

It is of importance to note the reader that all outcomes presented in this chapter depend on the assumptions made for the input values. For example, assumed is that charging infrastructure costs double when the amount of chargers or charging power doubles. However, in practice this is much more complex to determine: adding 3 chargers to an amount of 6 chargers may not increase infrastructure costs with 50% if the additional chargers are accommodated to existing transformer houses. Similarly, if there is sufficient electric capacity at certain terminal locations, doubling the charging power may be less costly than what is assumed in this study. More assumptions are made regarding operational costs and incomes, however, due to time constraints there has been varied only with the electricity, diesel and Li-Ion battery prices. Considering the TCO outcomes as accurate values may hence be misleading; instead, the outcomes presented merely serve as getting an order of magnitude to what extent battery-electric AGVs become financially feasible compared to diesel AGVs, which is the main subquestion to be answered in this chapter.

8

Conclusions and recommendations

This chapter aims at summarizing the performed research, discussing its main limitations and providing recommendations for the problem owner regarding the main research question and for future research possibilities. More specifically, section 8.1 provides answers to the subquestions and main research question of this study, after which section 8.2 discusses the main limitations of the performed research. Sections 8.3 and 8.4 end this chapter by providing recommendations for further research and for the problem owner respectively.

8.1. Conclusions

Brownfield container terminals are currently deploying diesel powered AGVs only for 24/7 container transport between the quay cranes at water side and the stacking cranes at land side. As studied by Van Duin and Geerlings (2011), diesel AGVs pollute by far the most carbon dioxide when compared to other equipment at container terminals in the Netherlands. Looking at the trends in formal legislation and market developments towards more sustainability due to increasing pressure on governments and the industry, these diesel AGVs are most likely to become outdated and taken on first in terminal's environmental policy and its corresponding AGV replacement program. In order to anticipate on future regulations, brownfield container terminals are conducting research on battery-electric AGVs, an emerging, zero-emission alternative to diesel AGVs. While battery-electric AGVs are environmentally friendly and thus appear to be a promising alternative for future legislation, the limited driving range and significantly longer replenishment times of the batteries compared to the current diesel AGVs' fuel tanks raises questions about the operational feasibility of deploying electric vehicles, especially in transport systems running 24 hours a day. With ports being the main sea entrances to continents, frequent charging of a port's vehicle fleet may lead to higher downtimes, which is highly undesirable as container transport is crucial for the total terminal productivity. Next to operational concerns, battery-electric AGVs also require higher investment costs in both vehicles and charging infrastructure when compared to diesel AGVs. Although electric propulsion is expected to result in lower operational costs due to the potential reduction in fueling and maintenance costs, brownfield terminal operators do not know if these fuel and maintenance savings over an electric AGV's lifetime outweigh the higher initial investment costs in batteries and infrastructure. This lack of knowledge on the operational and financial feasibility of battery-electric AGVs compared to their current diesel AGV fleet has created a bottleneck for brownfield terminal operators to make a well funded decision whether or not to purchase battery-electric AGVs for their next AGV replacement program.

From literature, a clear knowledge gap is observable regarding the operational and financial feasibility of implementing battery-electric AGVs at brownfield container terminals. Therefore, the aim of this study was to fill this knowledge gap in order to contribute to solving the future challenge for brownfield terminal operators regarding deploying battery-electric AGVs for their quay-stack transport. Taking the northern side (DDN) of the ECT Delta Terminal, the largest deep sea container terminal of Europe, as a research object, this study's main research question was:

Is it operationally and financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?

In order to answer the main research question, several subquestions have been formulated:

1. How are diesel AGVs currently operated during daily transport operations at the Delta Terminal and how is tanking fitted into this process?
2. Where in the AGV operational process occur opportunities for battery charging?
3. Which design of the AGV charging process can be used for further evaluation based on brownfield terminal operator's requirements and constraints?
4. How does the design influence the operational performance when compared to diesel AGVs?
5. To what extent is the design financially feasible when compared to diesel AGVs?

By using an adapted version of the systems engineering approach of Sage and Rouse (2009) as main research approach, three phases were sequentially traversed in order to answer the formulated research questions:

1. **Research object analysis**, in which the current state in container transport operations were analyzed. By operationalizing the AGV operational process, the most promising moments and locations for battery charging were obtained and subsequently used as input into the design phase.
2. **Development of alternative designs and selection**, in which functional designs of the AGV charging process were generated by means of a morphological chart. Based on predefined design requirements and constraints from the perspective of the terminal operator, a selection was made from the list of developed alternatives.
3. **Development of tests and testing the selected alternatives**, in which selected designs were evaluated on their operational and financial feasibility by means of simulation and a total costs of ownership analysis.

In the remainder of this section, answers are given to the subquestions after which the main research question is answered.

1. How are AGVs currently operated during daily transport operations at the Delta Terminal and how is tanking fitted into this process?

This study considers the water side of the DDN only; looking at Figure 8.1, encompassing the area in between the quay (bottom side) and the stack (top side). AGVs drive within this area in a grid structure, i.e. rectangularly, from the quay cranes (QC) to the automated stacking cranes (ASC) and vice versa with either a container on top or empty. Whereas the AGV elements can be modeled as closed systems, QCs and ASCs require to be modeled with interactions to the quay and stack area respectively. AGVs can either perform a discharge or loading trip: when discharging, an AGV first drives empty to a QC (black line in Figure 8.1), where it loads a container on top, after which the AGV drives loaded to the corresponding ASC to unload its container (green line in Figure 8.1). When performing a loading trip, the AGV drives empty to an ASC, gets a container on top and then drives loaded to the destination QC, where its container is being loaded onto the ship.

Regarding AGV control, central control is currently being applied at the Delta Terminal and at most other deep sea container terminals by means of a Terminal Operation System (TOS), which assigns AGVs to discharge/loading containers, sets routes to be followed by the AGVs and provides interaction with other terminal equipment, i.e. QCs and ASCs. Main advantages of central control over decentral control (e.g. by the AGVs themselves) are the possibility to reach a system optimum and to fully control the system (Ramadge and Wonham, 1989). However, disadvantages lie in the computational complexity for the TOS of dispatching all AGVs and in the risk of total terminal shutdown in case the central controller fails its task (Sycara, 1998).

Finally, AGVs receive a tanking notification in case their fuel load drops below 200 liters diesel of a total capacity of 1200 liters. Under the condition that a tanking spot is unclaimed and the AGV is not assigned to any discharge or loading container, the central TOS decides to let the AGV drive to the tanking spot (red dotted line in Figure 8.1), located at the edge of the operational area. Tanking on average takes 5-10 minutes.

2. Where in the AGV operational process occur opportunities for battery charging?

Analyzing a large data set of AGV time stamps led to the results as depicted in Figure 8.2. From starting a transport job (i.e. start driving empty to an assigned container) until starting another one, an AGV usually performs three actions: it is actively transporting containers from the quay to the stack side and vice versa, it is waiting for either the QC or ASC to load or unload their container on top or it is idling at an ASC Transfer

Figure 8.1: AGV movements during a discharge trip in black and green and during tanking in red

Point (TP) in between two subsequent transport jobs. It was observed that AGVs are either idling or waiting at a QC or ASC TP for a significant share of the total AGV cycle time. AGV waiting times under the QCs for (un)loading a container and waiting times at an ASC TP before driving to a QC (either loaded or unloaded) take up on average 7.5 and 7 minutes respectively on a total AGV cycle time of 30 minutes. When considering other waiting times, e.g. the waiting time at a prepositioning ASC before driving to a QC, this share further increases to two-third of the total AGV cycle time. Moreover, the average idle time in between two transport jobs is 13 minutes, which is about 30% of the total AGV time. From this analysis, it can thus be concluded that most opportunities for future battery charging occur at the ASC TPs and when queuing in the QC lane; at the ASC TPs both waiting and idle times could effectively be used for battery charging while in the QC lane only waiting times for (un)loading containers could be used for charging.

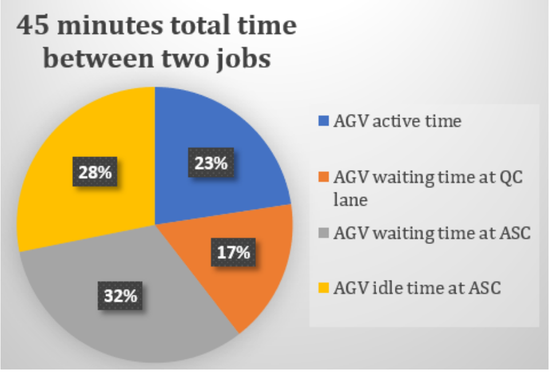


Figure 8.2: Total AGV time distribution in active, waiting and idle time

3. Which design of the AGV charging process can be used for further evaluation based on brownfield terminal operator's requirements and constraints?

By means of a stakeholder analysis, it was found that brownfield terminal operators' logistical and financial departments are not triggered yet to cooperate in the acquisition of battery-electric AGVs due to the unknown impact of the battery charging process on their operations and finance. Scoping the design towards the future battery-electric AGV charging process only, this study's main design requirements are:

1. Incorporating the AGV charging process into the operational process should lead to equal operational performance compared to the current diesel AGV fleet
2. Implementing a battery-electric AGV fleet and its charging process should lead to equal or lower total costs of ownership compared to the current diesel AGV fleet

These requirements are operationalized into measurable quantities, i.e. criteria:

Operational criteria

Criterion 1: Vessel turnaround times in hours/vessel

Criterion 2: QC-AGV interaction in % of QC moves waiting for AGVs %

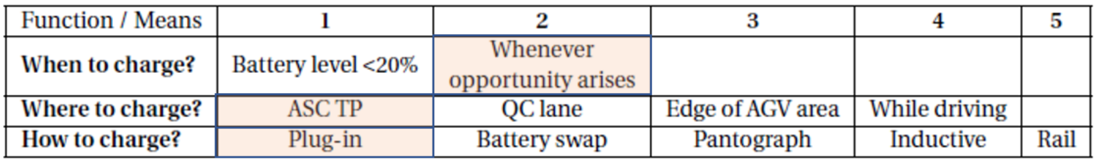
Criterion 3: QC productivity in moves/hour/QC

Financial criteria
Criterion 1: Capital expenditures of infrastructure and AGVs over a predefined time horizon in €
Criterion 2: Maintenance expenditures of infrastructure and AGVs in €
Criterion 3: Fueling expenditures of AGVs in €
Criterion 4: Terminal downtime expenditures in €

Furthermore, the constraints with which AGV charging designs must comply are:

1. the AGV charging process shall never hinder QC operations
2. the charging technique used shall not cause damage to other terminal equipment and communication systems
3. the charging infrastructure shall fit within the current terminal layout
4. the charging technique used shall be available on the market

By functionally decomposing the AGV charging process into *when*, *where* and *how* to charge, alternatives have been trawled for each of these system functions into a morphological chart (see Figure 8.3). By combining alternatives over the system functions, a complete AGV charging process design is generated. After evaluating all designs on the predefined requirements and constraints, **opportunity plug-in charging at the ASC TPs** turned out to be the most promising AGV charging process design and is therefore selected for further evaluation on its operational and financial feasibility by means of simulation and a total costs of ownership analysis.



Function / Means	1	2	3	4	5
When to charge?	Battery level <20%	Whenever opportunity arises			
Where to charge?	ASC TP	QC lane	Edge of AGV area	While driving	
How to charge?	Plug-in	Battery swap	Pantograph	Inductive	Rail

Figure 8.3: Morphological chart with the selected design of the AGV charging process: opportunity plug-in charging at the ASC TPs

4. How does the design influence the operational performance when compared to diesel AGVs?

For the assessment of the transport performance, the operational criteria of subquestion 3 have been used. As the main objective of this subquestion is to find out if electric charging is operationally feasible at brownfield terminals in general and at the ECT Delta Terminal in particular, variables influencing the operational performance of electric vehicles have been consequently looked up in literature. From this literature research, the *number of AGVs*, *battery capacity*, *charging power* and *number of chargers* turned out to be decisive for the determination of the operational performance of electric AGVs. The selected AGV charging design of the previous subquestion, opportunity plug-in charging at the ASC TPs, has consequently been experimented with by varying the above mentioned variables on a predefined range by means of discrete event simulation. The results of the simulation experiments indicate that the number of AGVs, charging power and number of chargers have a significant effect on the operational performance of deep sea container terminals. For the DDN, regarding the number of AGVs a convex relation with terminal operational KPIs is observed which flattens at 80 AGVs; from this point marginal improvement in turnaround times and terminal productivity is observed. Looking at differences in battery capacities, for the DDN no increase in terminal performance is perceived when increasing the battery size; 60 kWh batteries turn out to perform equally effective as 220 kWh batteries. Apparently, the idle time in between two jobs, 14.84 minutes, is enough to charge the AGV to a sufficient battery level, as is confirmed by the average charging time of 11.09 minutes. Moreover, when looking at the required charging power and number of chargers, 300 kW and 6 chargers are sufficient for minimal deterioration in terminal performance.

From the experiment results, 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 charging spots turned out to perform operationally equal to the current diesel AGV fleet. By having conducted a future state analysis on this design configuration, in which current container arrivals have been sequentially increased with 20% and 40% to assess the robustness of a battery-electric AGV fleet, it was observed that battery-electric AGVs opportunity plug-in charged at the ASC TPs prove to be resilient for future growth in container transshipment.

5. To what extent is the design financially feasible when compared to diesel AGVs?

To answer this subquestion, the cost elements of Schmidt et al. (2015), which are visualized in Figure 8.4, have been used as input into a Total Costs of Ownership (TCO) analysis, which takes into account all costs that occur during the lifetime of an AGV. Additionally, downtime costs, for which the delays in deep sea vessel turnaround times have been monetized, and salvage incomes from AGVs and batteries are included to complete the list of costs.

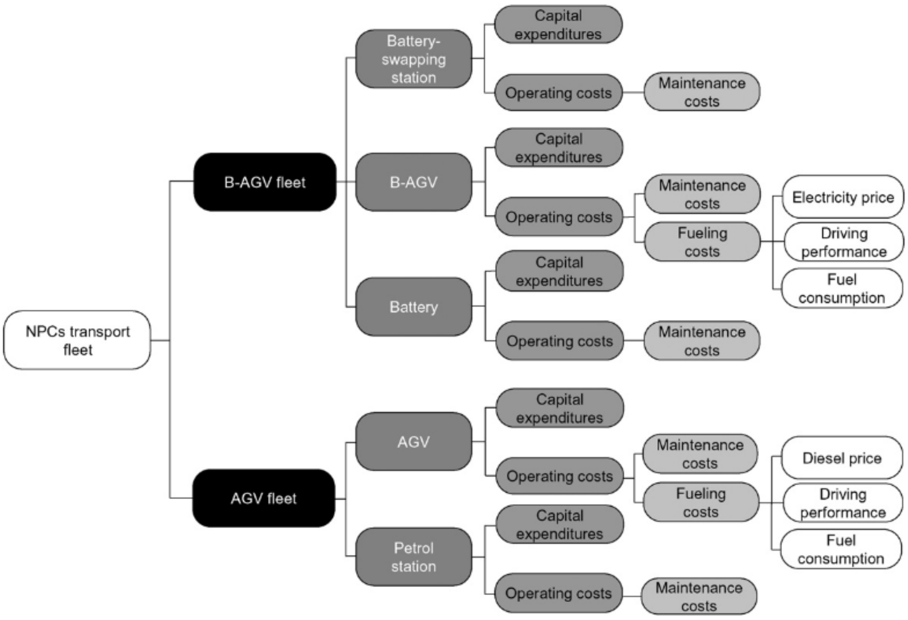


Figure 8.4: Cost elements of diesel powered and battery-electric AGVs (Schmidt et al., 2015)

Using a time horizon of 15 years, a fully battery-electric AGV fleet has been financially compared to the current diesel AGV fleet. Therefore, a two stage experimental analysis has been conducted: Therefore, a two stage experimental analysis has been conducted: in the first stage, similar to the operational evaluation, it is experimented with the number of AGVs, battery capacity, charging power and number of chargers in order to determine which design configuration results in the lowest cost difference with diesel AGVs whilst ensuring operational feasibility. The second stage subsequently tested this most promising design configuration by varying with the diesel, electricity and battery price levels in order to determine under what conditions a battery-electric AGV fleet opportunity plug-in charged at the ASC TPs is financially feasible when compared to the current state with diesel AGVs. For the first stage, the configuration that turned out to be most cost effective at the DDN side of the Delta Terminal comprises 75 AGVs, 160 kWh batteries, 300 kW charging power and 6 chargers installed evenly along the ASC TPs: the extra lifetime costs compared to a diesel AGV fleet are equal to 1,940,822 euros. Consequently, this configuration has been evaluated further on its sensitivity to changes in diesel, electricity and Lithium-Ion battery prices, cost parameters which are likely to vary in the (near) future.

From this scenario analysis, it was observed that especially future increases in diesel price result in a positive TCO for battery-electric AGVs. This is explained by the fact that, unlike AGV maintenance costs, improvement in operational expenditures is mostly made by the reduction in fueling costs, which cause around 25% of the total costs of ownership of diesel AGVs while only 6% of the battery-electric AGVs' lifetime costs. With this in mind, it can easily be reasoned that especially the diesel price is a decisive factor in determining the financial feasibility of battery-electric AGVs when compared to diesel AGVs rather than the electricity price: slight increases in diesel prices substantially influence the TCO of diesel AGVs and thus the cost difference with electric vehicles. The Li-Ion battery price appears not be a crucial factor for the financial feasibility as even with current Li-Ion price levels battery-electric AGVs prove to be financially feasible and viable over diesel AGVs. Hence, overall it can be concluded that, assuming that the current trend in diesel and electricity prices will continue in the (near) future, battery-electric AGVs prove to be a (far) more cost-effective alternative than their diesel counterpart.

Is it operationally and financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals?

Taking the northern side of the ECT Delta Terminal as a case, it was found that, using opportunity plug-in charging at the ASC TPs as a functional design of the AGV charging process, battery-electric AGVs prove to be an operationally and financially feasible alternative to diesel AGVs: operationally under the condition that a sufficient amount of AGVs, charging power and chargers are installed and financially under the condition that the current trend in diesel and electricity prices will continue in the (near) future. As environmental legislation for heavy-duty vehices becomes more stringent while there is a decreasing trend in electricity prices, battery-electric AGVs are most likely to become profitable for deployment at deep sea container terminals. This profitability is enforced by the reduction in local emissions.

8.2. Limitations of the research

Main limitation of this research is its scope: as a comprehensive approach has been applied for a large study object, several assumptions have been made throughout the study in order to reduce the degrees of freedom. The most critical assumptions and their limitations are the following:

- Regarding the simulation model, instead of modeling the physical driving of AGVs, an average speed has been used which accounts for vehicle interactions on the way. However, when AGVs will be opportunity charged at the ASC TPs, the vehicle density, and thus the number of crossings, will increase at these locations. Consequently, the simulation model may *overestimate* the logistical feasibility of charging in the loop as no potential increase in congestion has been incorporated. Also, as battery-electric AGVs prove to be more energy efficient with many start-stops than their diesel counterpart, the simulation model may consequently *overestimate* the energy consumption of an electric vehicle fleet. Finally, no load and discharge plans are incorporated into the simulation logic; instead, QCs and ASCs competitively request for AGVs, the scarce resource. By implementing load and discharge plans into the simulation model, one could find simulation outcomes which differ from those presented in this research in such a way that a global optimum may be found (instead of local optima).

- Regarding the simulation experiments and total costs of ownership analysis, a base case has been defined for the selected AGV charging process design from where the number of battery-electric AGVs, battery capacity, charging power, amount of chargers and opportunity charge threshold have been sequentially varied in order to gain insight into their individual contribution to the overall operational and financial performance. Consequently, the obtained ’optima’ for the studied variables cannot be considered in isolation from this base case. When also changing the other variables, another optimum will be found. To put it briefly, the considered designs of freedom made it very complex to find an ’optimal’ design configuration which results in the best operational and financial viability. However, as this study’s main objective was to evaluate battery-electric AGV charging on its operational and financial **feasibility**, studying the most promising configuration only suffices.

- Several assumptions have been made for the TCO analysis for which time was lacking to perform a sensitivity analysis on all of them. For example, doubling the infrastructure costs when the amount of chargers or charging power doubles is mostly likely invalid and heavily depends on the current terminal’s electric capacity. Instead, there has been varied with the diesel, electricity and Li-Ion battery prices only. Furthermore, the net present value of costs have not been taken into account; when accounting for this *time value of cash*, battery-electric AGVs will become financially less feasible as the reduction in fueling costs weighs less heavily over the years while initial investment costs keep the same value. Moreover, varying the time horizon proves to be of influence on the financial feasibility of battery-electric AGVs, so will the reductions in carbon dioxide emissions be if it is decided to monetize these. To conclude, considering the TCO outcomes as accurate values may be misleading; instead, the outcomes presented merely serve as getting an order of magnitude to what extent battery-electric AGVs are a financially feasible alternative to the current diesel AGVs.

8.3. Recommendations for further research

The main limitation of this research, its scope, also paves the way for recommendations for further research. One could incorporate AGV-AGV interactions during driving in the developed simulation model and investigate the effects on the outcomes of this study. Also, instead of varying all design variables, i.e. number of AGVs, battery capacity, charging power, amount of chargers and opportunity charge threshold, one could decide to vary only one variable for which an optimal value *can* be found. The design variables varied in this study serve as an initial step, further research could extend the list of factors which are of influence on the operational and financial feasibility of battery-electric AGVs at brownfield container terminals. Finally, one could incorporate the net present value of costs into the TCO analysis and investigate its effect on the profitability of a battery-electric AGV fleet.

Since the field of electric charging AGVs at brownfield container terminals is unexplored, a lot of possibilities for further research exist. While this research considered the two evaluation criteria, operations and costs, with equal weight, one could evaluate AGV charging designs more extensively by performing a multi criteria analysis in which each design criterion is assigned a certain weight. Also, while this study incorporated both busy and non-busy periods into the simulation to resemble real-world terminal performance as much as possible, it might also be interesting to investigate how much AGVs, chargers, charging power etcetera are needed during peak moments. Since terminal operators purchase AGVs according to the demand during peak hours, it is interesting for further research to study the required battery-electric fleet size for these moments only.

As a final remark, this study explicitly considered container terminals as closed transportation system in which electric mobility is applied. Further research could extend the findings mentioned in this study to other closed transport systems, such as distribution centers and airports, in order to gain a better understanding of the operational and financial challenge the industry currently is facing regarding the trend towards sustainability.

8.4. Recommendations for the problem owner

Regarding the problem owner of this study, Europe Container Terminals, the following recommendations are given:

1. As ECT is considered a brownfield container terminal, space restrictions cause the operator to look for alternative charging techniques instead of battery swapping stations, which proved to be financially and operationally feasible at deep sea container terminals (Schmidt et al., 2015). Based on a requirements analysis, *opportunity plug-in charging at the ASC TPs* turned out to be most promising regarding brownfield operator's operational and financial requirements. Therefore, this AGV charging design alternative was selected for further evaluation on its operational and financial feasibility.

2. For the DDN side of the Delta Terminal, adding extra AGVs at the expense of purchasing more chargers seems to be the best strategy to reduce operational downtimes as AGV driving distances are rather short. For the DDE side of the Delta Terminal, the opposite is observed as relatively more vehicles must be bought to achieve the same operational performance when compared to the amount of chargers to be initially purchased (while the latter's unit price is lower).

3. The simulation outcomes indicated that for both sides of the Delta Terminal a ratio of 1 charger to every 20 AGVs proves to be a bare minimum to minimize deterioration in operational performance. Especially for the DDE, though, it is recommended to purchase substantially more chargers than this ratio (1 charger for every 6-7 battery-electric AGVs).

4. Battery-electric AGVs prove to be a significantly more profitable alternative than the current diesel AGVs under the condition that the current trends in rising diesel prices and decreasing electricity and Li-Ion battery prices continue in the (near) future. This profitability is more substantial for larger container terminals, i.e. the DDE.

9

Reflection on the performed study

This chapter ends this study by reflecting upon the value of the performed research within state-of-the-art literature and by critically discussing the graduation process of the past 7 months.

9.1. Reflection on scientific and practical relevance

As this study's main objective was to gain insight into the operational and financial feasibility of replacing diesel AGVs by battery-electric AGVs at brownfield container terminals, to the author's opinion the outcomes do contribute to a better understanding of this feasibility. In fact, because this is a heavily understudied research subject multiple exploratory analyses have been conducted with regard to the amount of extra AGVs needed, size of the batteries, charging power and location and amount of chargers. Instead of varying only one variable throughout the research, it was decided to vary all variables (one at the time) in order to gain insight into the individual contribution of each design variable to the operational and economical viability of the entire battery-electric AGV fleet. For specific cases with fixed settings, it becomes possible to optimize to only one variable if the defined research question allows the researcher to do so; this study's research question was merely an exploratory one.
By taking a systems engineering approach, it was ensured that the AGV charging design that has been evaluated does meet all design constraints predefined by this study's problem owner. As current literature on battery-electric AGVs at container terminals only considers greenfield terminals, in which the layout and the operational process to be deployed are variable, this study is, to the author's knowledge, unique as it takes into account the (complex) fact that brownfield container terminals face severe space and operational constraints, in which battery charging must fit, since charging is considered a subprocess of the main terminal process: container transport (operational process). Since diesel-powered AGVs are almost exclusively used at brownfield container terminals, taking these space and operational constraints explicitly into account provides brownfield operators a more realistic way of replacing their current diesel AGVs by zero-emission vehicles.

9.2. Reflection on the research process

Although the research process over the past seven months was initially well structured, the actual performance was not fully in line with the defined research scope. In fact, during this Thesis research I frequently faced a well-known characteristic of mine: I was a bit too ambitious and did more than necessary. This was because I really liked the topic and dived into many technical details while engaging with the field engineers and operators of ECT:

1. during the design phase, instead of providing a functional design of the AGV charging process only, I also provided a technical design ready for implementation at the Delta Terminal. Although I have put a lot of effort in this design, decided is to remove this piece from the report as it does not fit within this study's scope.

2. during the operational evaluation phase, instead of considering the DDN side of the Delta Terminal only, I also developed a simulation model of the larger side, the DDE, and subsequently experimented

with this model in order to check the validity of the DDN conclusions for even larger container terminals. The results of these experiments can be found in Appendix I.

3. during the financial evaluation phase, instead of considering the DDN side of the Delta Terminal only, I also considered the DDE and consequently performed a TCO analysis on this side of the Delta Terminal too. The results of these TCO experiments can also be found in Appendix I.

I am sure that if I would have stuck to this study's scope from the beginning, I would have finished much earlier. At the end, a wise and very useful lesson learned.

A

KPIs water side Delta Terminal

For the analysis of KPIs, several data sets have been consulted:

1. *AGV Waiting* data for both the DDN and DDE
2. *Discharge and load trips* for the DDN
3. *Load and discharge lists of ships* for the whole Delta Terminal
4. *AGV mileage* data for the whole Delta Terminal
5. other data sets provided by the Logistical Department

A.1. DDN

Starting with the *QC, AGV and ASC utilizations*, these values have been determined in consultation with ECT experts. The QC utilization oscillates between 60 and 70%, while AGV utilization approaches 75%. Figure A.1 shows the ASC land side and water side utilization for the months January until June 2018. As can be seen, the water side utilization, which is of interest for this study, fluctuates between 50 and 60%.

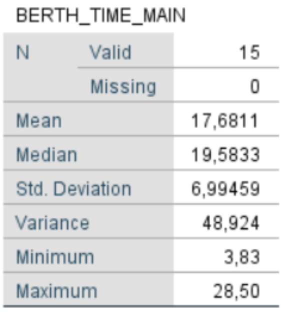
Item	KPI	Unit	jan-2018	feb-2018	mrt-2018	apr-2018	mei-2018	jun-2018
1,1	Landside (LS) ASC rate	mph	9,9	9,9	10,6	9,7	11,0	10,5
1,2	Waterside (WS) ASC rate	mph	13,7	13,6	14,8	13,8	15,5	15,1
1,3	ASC rate	mph	11,8	11,8	12,7	11,8	13,3	12,9
2,1	Landside ASC utilization	Busy-time %	37,2%	40,6%	44,6%	38,5%	47,5%	41,4%
2,2	Waterside ASC utilization	Busy-time %	49,5%	54,2%	61,1%	53,7%	62,7%	57,6%
2,3	ASC utilization	Busy-time %	43,4%	47,4%	52,9%	46,1%	55,1%	49,5%
3,1	Landside (LS) ASC Peak Period Rate	mph	12,5	12,3	13,1	12,1	13,2	12,9
3,2	Waterside (WS) ASC Peak Period Rate	mph	16,9	16,7	16,9	17,0	17,8	17,1
3,3	ASC Peak Period Rate	mph	14,4	14,1	14,8	14,1	15,1	14,8

Figure A.1: Water side ASC utilization in 2018

For the *average mooring time of ships*, a list of loads and discharges has been used for analysis. Figures A.2 and A.3 show the statistics of MAIN and BARGE ships; MAIN ships are characterized by large discharge and load sizes and thus longer mooring/berthing times, BARGES carry a substantially smaller amount of containers and thus the turnaround time is shorter. From the figures, it is obtained that MAIN turnaround times are on average 20.3 hours, while BARGE turnaround times count up to 3.3 hours.

The fraction of time QCs have to wait for AGVs and the average QC waiting time have been calculated; the results of this analysis are shown in Figures A.4 and A.5. Taking the median to avoid bias caused by extreme values, it can be seen that the QC waiting time is five times higher when containers are marked too late when compared to on-time containers.

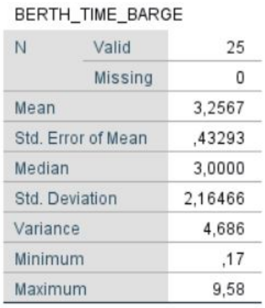
Finally, the loaded ride fraction is calculated by dividing the distance covered by an AGV while carrying a container by the total distance covered for three sequential months. The results are shown in Figure A.6. The



BERTH_TIME_MAIN

N	Valid	15
	Missing	0
Mean		17,6811
Median		19,5833
Std. Deviation		6,99459
Variance		48,924
Minimum		3,83
Maximum		28,50

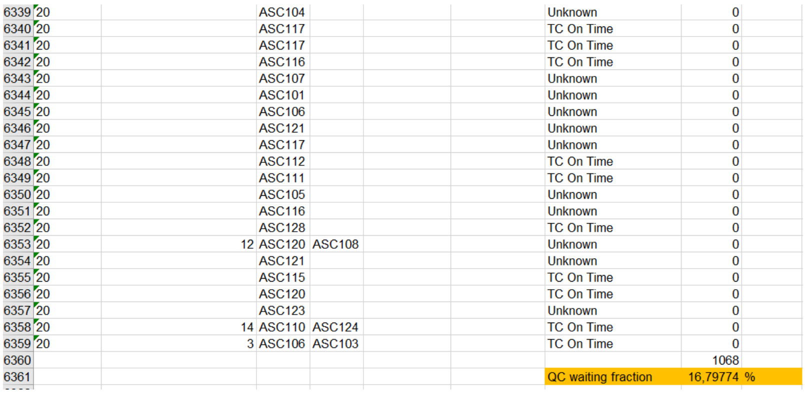
Figure A.2: MAIN ships turnaround time statistics in hours



BERTH_TIME_BARGE

N	Valid	25
	Missing	0
Mean		3,2567
Std. Error of Mean		,43293
Median		3,0000
Std. Deviation		2,16466
Variance		4,686
Minimum		,17
Maximum		9,58

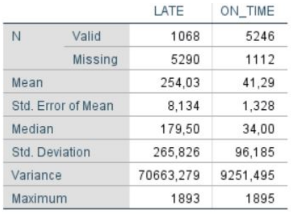
Figure A.3: BARGE ships turnaround time statistics in hours



6339	20		ASC104			Unknown	0	
6340	20		ASC117			TC On Time	0	
6341	20		ASC117			TC On Time	0	
6342	20		ASC116			TC On Time	0	
6343	20		ASC107			Unknown	0	
6344	20		ASC101			Unknown	0	
6345	20		ASC106			Unknown	0	
6346	20		ASC121			Unknown	0	
6347	20		ASC117			Unknown	0	
6348	20		ASC112			TC On Time	0	
6349	20		ASC111			TC On Time	0	
6350	20		ASC105			Unknown	0	
6351	20		ASC116			Unknown	0	
6352	20		ASC128			TC On Time	0	
6353	20	12	ASC120	ASC108		Unknown	0	
6354	20		ASC121			Unknown	0	
6355	20		ASC115			TC On Time	0	
6356	20		ASC120			TC On Time	0	
6357	20		ASC123			Unknown	0	
6358	20	14	ASC110	ASC124		TC On Time	0	
6359	20	3	ASC106	ASC103		TC On Time	0	
6360							1068	
6361						QC waiting fraction	16,79774	%

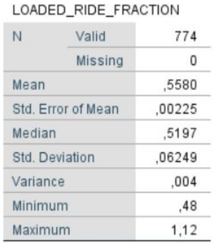
Figure A.4: Average percentage of QCs waiting for AGVs

empty ride fraction can be retrieved by taking the complement of 0.5580, which equals 0.4420. For efficiency purposes, this value is preferred to be minimized.



		LATE	ON_TIME
N	Valid	1068	5246
	Missing	5290	1112
Mean		254,03	41,29
Std. Error of Mean		8,134	1,328
Median		179,50	34,00
Std. Deviation		265,826	96,185
Variance		70663,279	9251,495
Maximum		1893	1895

Figure A.5: Average waiting time of QCs for AGVs in seconds for both on time and too late containers



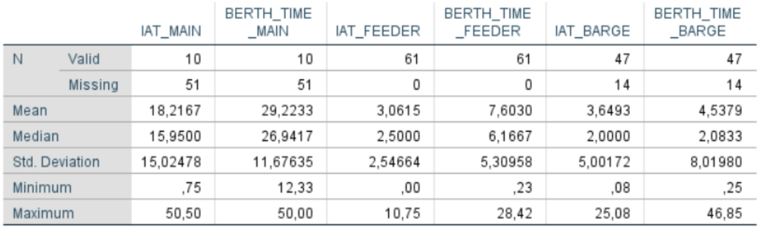
LOADED_RIDE_FRACTION

N	Valid	774
	Missing	0
Mean		,5580
Std. Error of Mean		,00225
Median		,5197
Std. Deviation		,06249
Variance		,004
Minimum		,48
Maximum		1,12

Figure A.6: Loaded ride fraction of total trips made (dimensionless)

A.2. DDE

For the DDE, all KPIs are nearly the same as for the DDN except from the mooring time of vessels. While the DDN distinguishes MAINS and BARGES, for the DDE one ship type is added: FEEDERS, which are characterized by container discharges and loads larger than for BARGES but smaller compared to MAINS. Figure A.7 shows the statistics of MAIN, FEEDER and BARGE ships' turnaround and inter arrival times; while MAIN ships have very high turnaround and inter arrival times due to very large container discharge and load sizes, BARGES reflect the opposite.



		IAT_MAIN	BERTH_TIME_MAIN	IAT_FEEDER	BERTH_TIME_FEEDER	IAT_BARGE	BERTH_TIME_BARGE
N	Valid	10	10	61	61	47	47
	Missing	51	51	0	0	14	14
Mean		18,2167	29,2233	3,0615	7,6030	3,6493	4,5379
Median		15,9500	26,9417	2,5000	6,1667	2,0000	2,0833
Std. Deviation		15,02478	11,67635	2,54664	5,30958	5,00172	8,01980
Minimum		,75	12,33	,00	,23	,08	,25
Maximum		50,50	50,00	10,75	28,42	25,08	46,85

Figure A.7: MAIN, FEEDER and BARGE ships' turnaround and inter arrival times in hours for the DDE

B

Load/discharge timeline AGVs

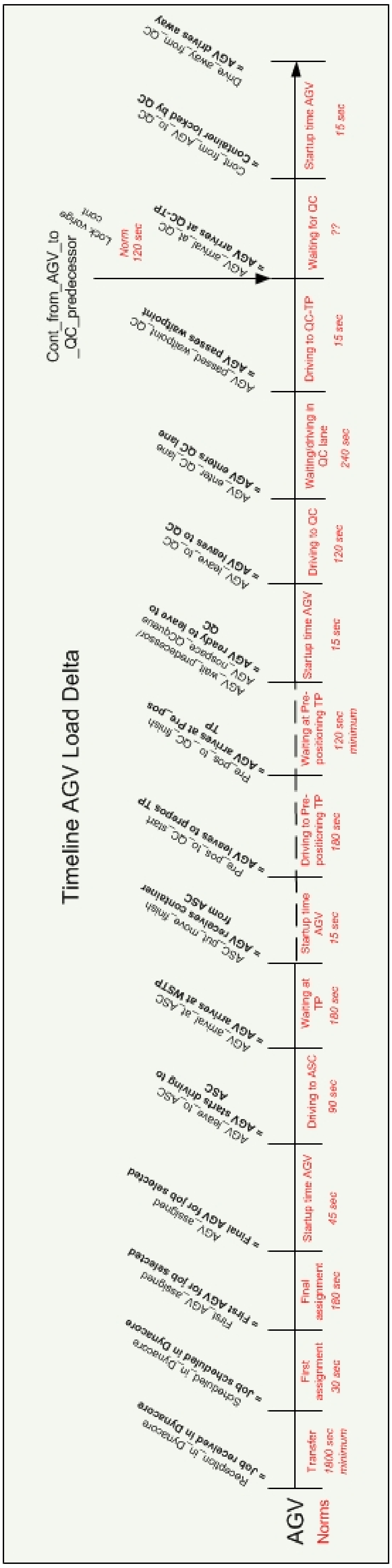


Figure B.1: AGV Load Timeline at the Delta Terminal

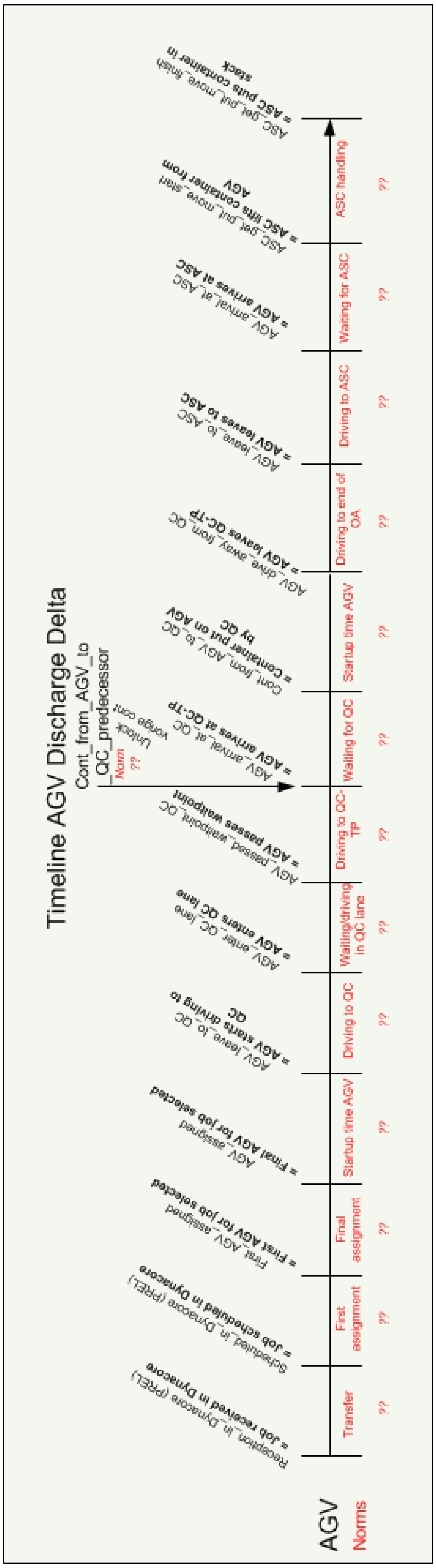


Figure B.2: AGV Discharge Timeline at the Delta Terminal

C

Stakeholder analysis

From interviews held with various departments (see Appendix J for the expert references), the objective tree as depicted in Figure C.1 is constructed. An objective tree maps the most important objectives of a stakeholder (or stakeholders) and operationalizes these to a measurable level by asking 'what does that imply?' (Enserink et al., 2010). From the objective tree, criteria to be used for assessment of charging designs are obtained, which are shown in the bottom row. The white box reflects the criteria of I&E, blue boxes the criteria of LD, the red boxes the criteria of FD and the light grey boxes the criteria of TOD. In this study, the focus is merely on the criteria of I&E, LD and FD; TOD criteria regarding an improved labour environment are expected to be satisfied as electric AGVs will be zero-emission and zero-noise. Moreover, the increasing transport demand in the future is expected to compensate the lower maintenance frequency of electric AGVs when compared to the current diesel fleet.

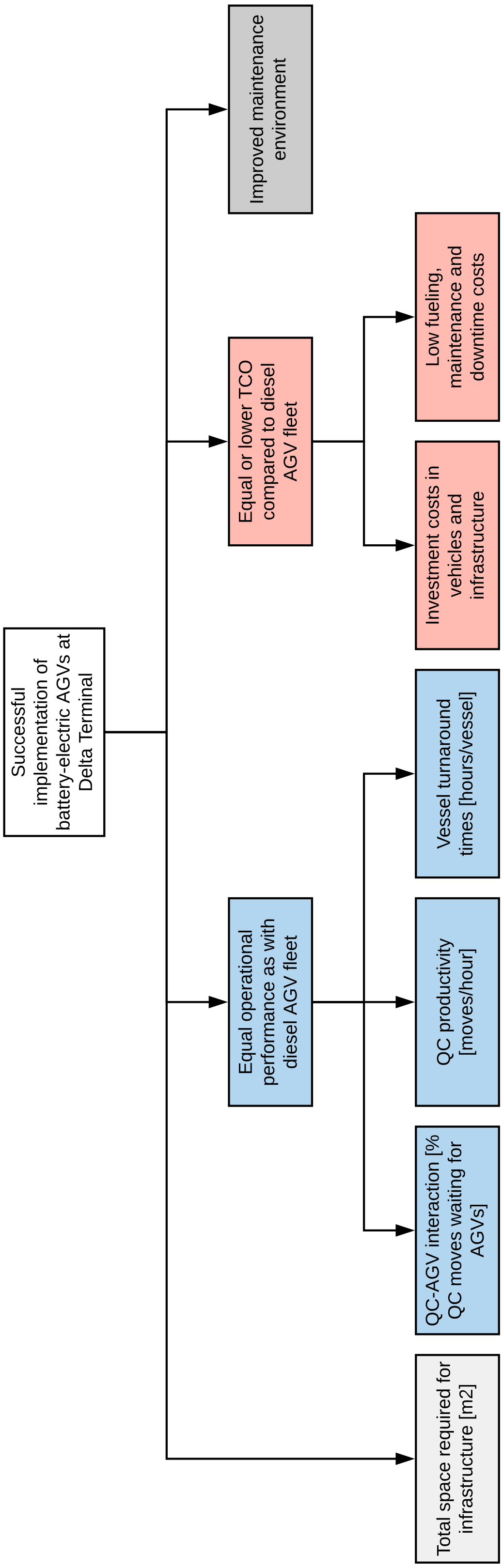


Figure C.1: Overview of ECT departments' objectives

D

Detailed layout of DDN and DDE

The Figures D.1 and D.2 below show the AGV operational area in green, the tanking area in yellow and the maintenance and testing area in red; the horizontal rows are the ASC container stacks. In between the red and green zone in Figure D.1, Building 34 is located; in between the red and yellow zone in Figure D.2, Building 26 is located. It must be noted, though, that the green area is not fully reachable by AGVs. Figure D.3 shows a real-time Graphical User Interface of the DDN, in which red blocks are AGV forbidden zones. These zones are also located on the water side terminal area and exist because of the movement of the QCs according to the length of the mooring ship. To prevent collisions between AGVs and QCs, dedicated QC entering zones for AGVs are assigned by the TOS.

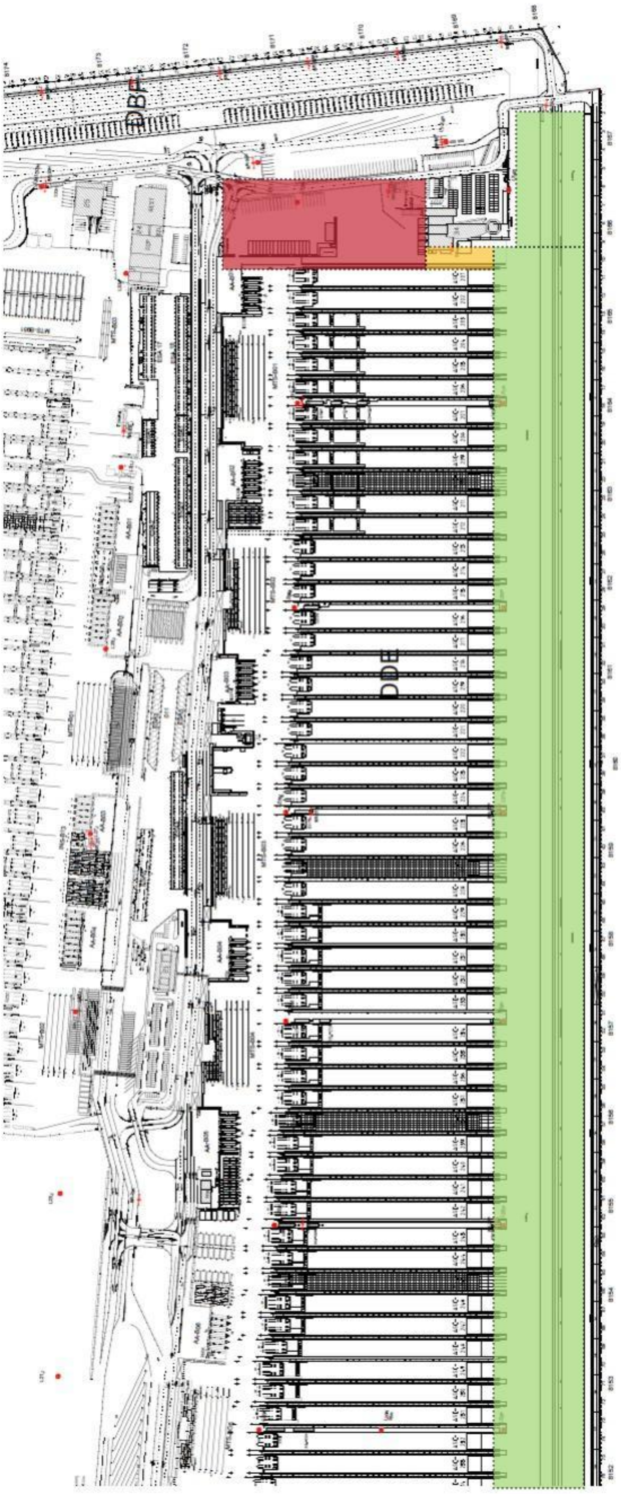


Figure D.1: Layout of the DDE with AGV operational zone in green, tanking area in yellow and AGV forbidden area (maintenance and testing) in red

Figure D.2: Layout of the DDN with AGV operational zone in green, tanking area in yellow and AGV forbidden area (maintenance and testing) in red

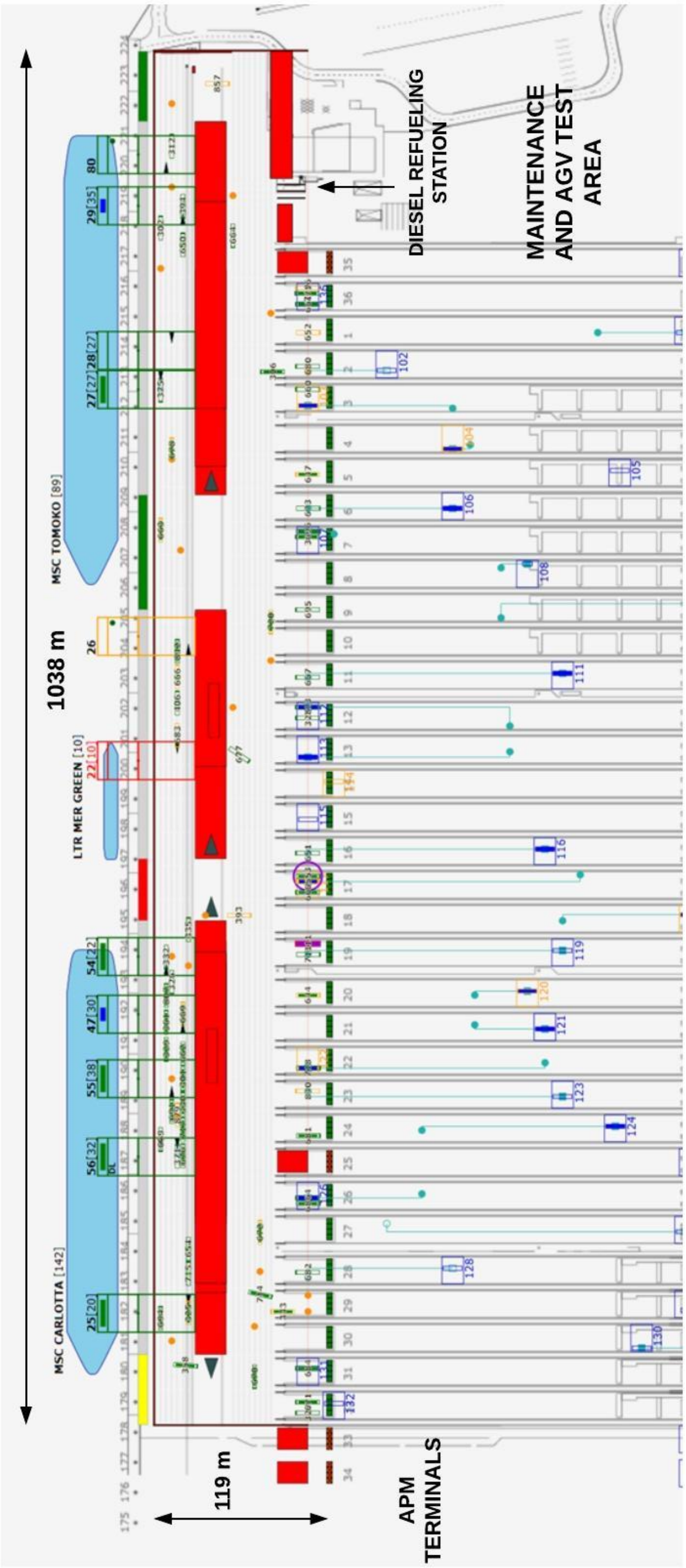


Figure D.3: Graphical User Interface of the DDN, where the red blocks reflect AGV forbidden areas

E

Chargers on the market

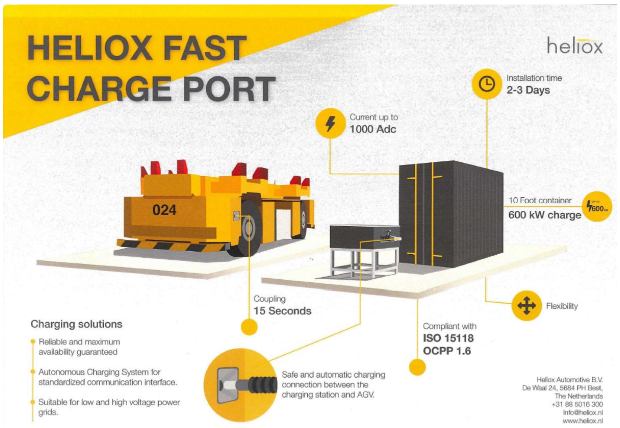


Figure E.1: Heliox plug-in charger with 600 kW charging power. The 10 foot container supplies the charging power to the smaller plug-in charger, which is 0.6 x 0.4 x 1 meter (l x w x h) in dimension.

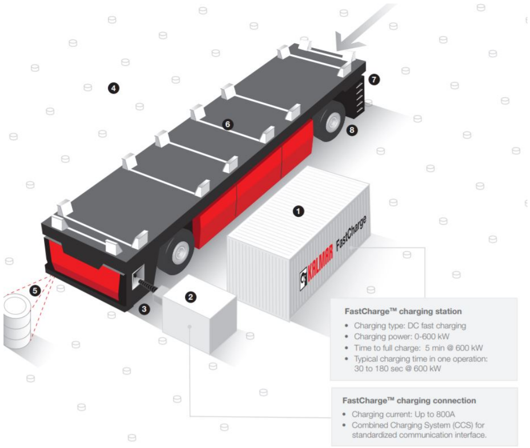


Figure E.2: Kalmar plug-in charger with 600 kW charging power; the dimensions are similar to Heliox' quick charger

F

Details of the simulation model

This appendix describes the details of the simulation model developed for the assessment of the operational feasibility of the selected AGV charging design *opportunity plug-in charging at the ASC TPs*.

F.1. Control cycles of simulation elements

For the overall distributed control architecture, the reader is referred to Figure 5.13. In this section, the individual agent's control cycles are discussed.
Starting with the control cycle of the Ship Generator, its main objective is to spawn ships with corresponding discharge and load sizes according to an inter arrival time and load and discharge distribution which have been fitted on ECT data. The Ship Generator can be either actively assigning ships to a *ShipsWaiting* queue or to an idle QC Group. If the sampled inter arrival time has elapsed, the Ship generator becomes active; the Ship Generator only interacts with the QC Group.

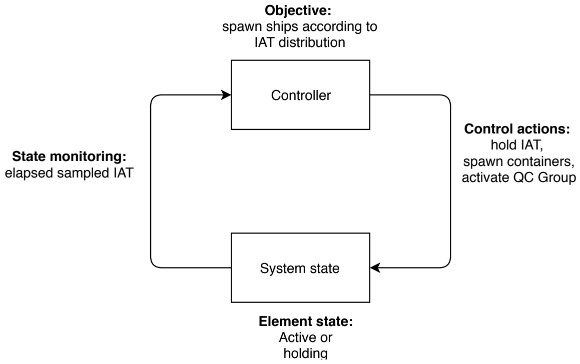


Figure F.1: Control cycle of the Ship Generator

For the QC Group, the control cycle is merely coordinatory: most of the actions performed by the QC Group resemble the activation of QCs after a certain condition has been meet. Moreover, QC Groups distribute containers to be loaded onto the mooring ship over the ASCs once the ship has been fully discharged and subsequently destroy ships once these have been fully loaded and have left the quay wall. Monitoring the discharge and load status of the ship is achieved by checking the lengths of *DischargeToBeHandled* and *LoadToBeHandled*: once these queue lengths are zero, the ship has been fully discharged and loaded respectively. The QC Group only interacts with its corresponding QCs and the Ship Generator.

The QC controller's main objective is to discharge mooring ships and to handle loaded AGVs that have arrived at a QC TP. For discharging a ship, the QC requests an AGV by checking the *AvailableAGVs* queue length and selecting the AGV that is nearest to the QC. If no AGVs are available, the QC becomes passive and is awakened by another QC, ASC or tanking station which has just handled an AGV. Furthermore, when the QC has

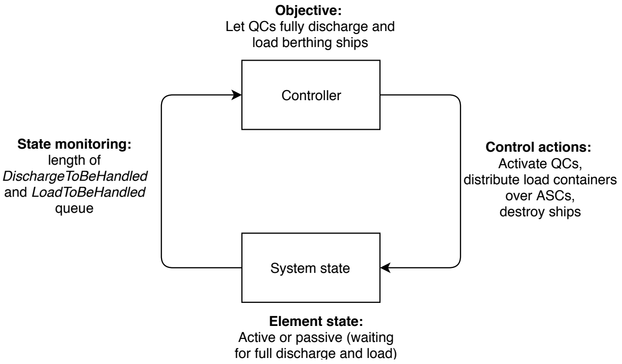


Figure F.2: Control cycle of the QC Group

handled an AGV's container, it assigns the AGV either for tanking, for another QC or ASC waiting for available AGVs or lets the AGV enter *AvailableAGVs* queue after which the AGV becomes idle. Checking whether there are loaded AGVs waiting for handling by a QC is done by looking at the length of the QC's specific *AGVsWaiting* queue. The QC interacts with its QCGroup, AGVs and tanking stations.

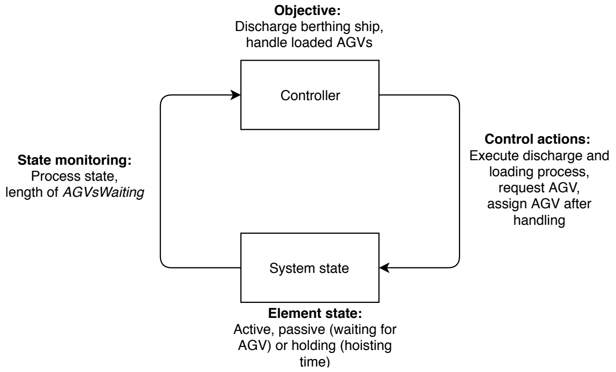


Figure F.3: Control cycle of the QC

The AGV controller has as main objective to transport their assigned containers and to drive to a tanking station in case being assigned by a QC or ASC. Its main control actions are activating or resuming the QC, ASC or tanking stations once arrived at their TPs (with or without container) and holding the precalculated travel times, either to a QC, ASC or tanking station. As a consequence, AGVs can either be active and holding their correct travel time or passive and waiting for the other equipment to either load or unload the AGV. The AGV controller monitors the elapsed travel time in case the AGV's state is holding: when the elapsed travel time equals the precalculated travel time, the AGV becomes active and activates or resumes the other equipment. Also, the AGV checks up front if it is present in the global *GoTanking* queue: if this is indeed the case, the AGV holds the correct travel time to the nearest available tanking station. The AGV interacts with QCs, ASCs and tanking stations.

The ASC controller has much similarities with its QC counterpart as they both request AGVs and assign them after handling to the correct terminal equipment. However, instead of monitoring the discharge and load status of the mooring ship, the ASC checks the length of its own *StackContainersWaiting* queue in order to get rid of its container stack. While the most used selection principle in the simulation model is *First In First Out*, the selection of containers from the *StackContainersWaiting* queue is done by checking the arrival time of the container's corresponding ship. The container with the earliest ship arrival time is selected for transport in order to minimize the mooring times of the ships. The ASC interacts with AGVs and tanking stations.

Finally, the Tanking procedure controller has as main objective to tank the AGVs that have arrived at the tanking stations. By holding the tanking time, the fuel loads of the AGVs are set to their maximum (i.e. 1200 liters diesel). After tanking, it is checked whether there are QCs or ASCs waiting for available AGVs. If this is

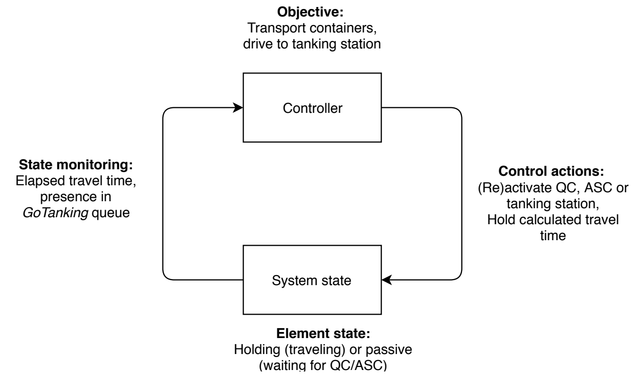


Figure F.4: Control cycle of the AGV

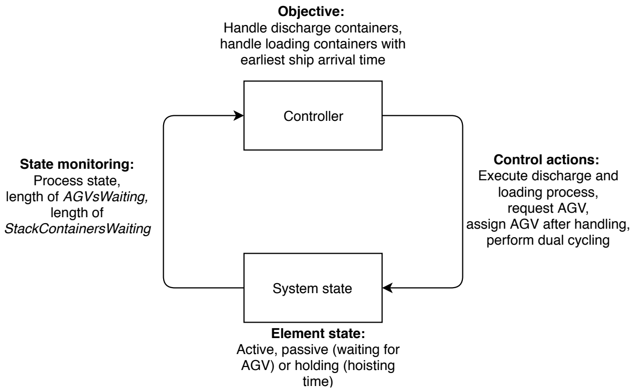


Figure F.5: Control cycle of the ASC

the case, the Tanking Station controller reactivates the QC or ASC and lets the AGV drive to this QC or ASC (by activating the AGV process). If not, the Tanking controller lets the AGV enter *AvailableAGVs*. Consequently, the tanking station only interacts with AGVs, ASCs and QCs.

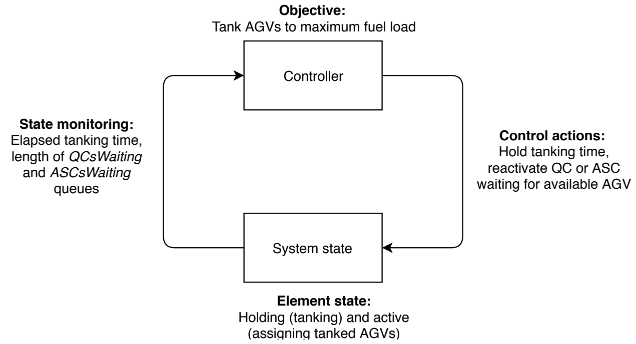
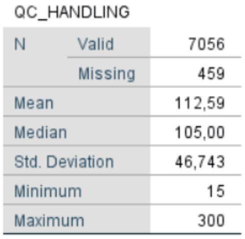


Figure F.6: Control cycle of the Tanking Station

F.2. Input parameters simulation model

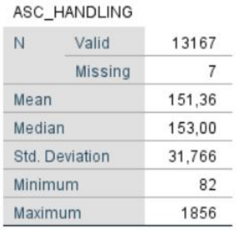
Figures F.7, F.8, F.9 and F.10 show the outcome of the data analysis which are used as input into the simulation model. It is observed that handling times of QCs are more stochastic (i.e. have a higher standard deviation) than the handling times of ASCs due to the manual operation of QCs (while ASCs are automatically operated).



QC_HANDLING

N	Valid	7056
	Missing	459
Mean		112,59
Median		105,00
Std. Deviation		46,743
Minimum		15
Maximum		300

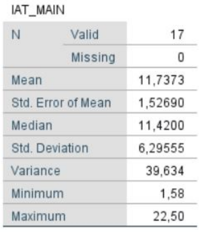
Figure F.7: QC handling time statistics in seconds



ASC_HANDLING

N	Valid	13167
	Missing	7
Mean		151,36
Median		153,00
Std. Deviation		31,766
Minimum		82
Maximum		1856

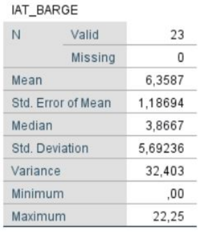
Figure F.8: ASC handling time statistics in seconds



IAT_MAIN

N	Valid	17
	Missing	0
Mean		11,7373
Std. Error of Mean		1,52690
Median		11,4200
Std. Deviation		6,29555
Variance		39,634
Minimum		1,58
Maximum		22,50

Figure F.9: Inter arrival time statistics of MAINS in hours for the DDN



IAT_BARGE

N	Valid	23
	Missing	0
Mean		6,3587
Std. Error of Mean		1,18694
Median		3,8667
Std. Deviation		5,69236
Variance		32,403
Minimum		,00
Maximum		22,25

Figure F.10: Inter arrival time statistics of BARGES in hours for the DDN

F.3. Verification of the diesel AGV simulation model

Checking the correct working of the simulation model is done by means of *Hand event tracing*, with which during simulation run time all events are manually traced using the TOMAS Trace Option. *Seed indepence tests*, with which seeds are varied across simulation runs to look for variety in simulation output, and *Comparison with analytical results*, where back-of-the-envelope calculations are used to check the simulation outcomes on order of magnitude. For the verification of the model, all input parameters must be fixed as stochasticity leads to outcomes which are impossible to calculate on beforehand; the set of deterministic input parameter values is shown in Figure F.1. It is decided to set the number of AGVs to 500 so there will always be an AGV available, which leaves out the complex effect of waiting (delays) on available AGVs. First, however, it is checked whether the simulation passes some general checks. These are:

- An infinite amount of AGVs should lead to no QCs and ASCs waiting for AGVs.
- The queue lengths of *QCsWaiting* and *ASCsWaiting* cannot be larger than zero if the length of the queue *AvailableAGVs* is larger than zero; this is due to the fact that there are AGVs available, which per definition should not lead to QCs or ASCs waiting for AGVs becoming available. Also, the queue lengths of *QCsWaiting* and *ASCsWaiting* cannot be larger than 10 and 34 respectively otherwise (in total 10 QCs along the quay wall and 34 ASCs along the stack side).
- AGV driving times in seconds from QC to ASC or from ASC to QC cannot exceed (1000 + 100 meters)/2.76 meters per second since 1100 meters is the maximum distance an AGV can cover per single trip.
- The *AvailableAGVs* queue length cannot be greater than the total amount of AGVs spawned during the initialization.
- An AGV can pick up at most 1 container at the time; similarly, QCs and ASCs can handle one container after another.

By adjusting the source code for tracing purposes of the above mentioned checks, it is concluded that the simulation model passes all checks.

F.3.1. Hand event tracing

For hand event tracing the TOMAS Trace option has been used; Figure F.11 graphically shows the TOMAS Trace view of the initialization of the simulation. Similarly, it is checked with this option how the elements

Table F.1: Deterministic input parameters used for the verification with, in bold, the inputs that have been fixed

	Parameter	**Value**	**Unit**	**Obtained from**
Topology	Size of terminal	1038 x 119	meters	Delta view
	# QCs per MAIN	4	-	QC data
	# QCs per BARGE	2	-	QC data
	# MAIN QC Groups	2	-	Delta view
	# BARGE QC Groups	1	-	Delta view
	Longitudinal separation QCs	50-75	meters	QC data
	# ASCs	34	-	Delta view
	Longitudinal separation ASCs	25	meters	Delta view
Operational	# AGVs	65	-	ECT experts
	Speed of AGV	2.76	meters/second	AGV and QC data
	Handling time QC	**2**	minutes	QC data
	Handling time ASC	**2.5**	minutes	ASC data
	Inter arrival time MAINS	**700**	minutes	Load and discharge data
	Inter arrival time BARGES	**380**	minutes	Load and discharge data
	Discharge size MAINS	**500**	containers	Load and discharge data
	Load size MAINS	**500**	containers	Load and discharge data
	Discharge size BARGES	**40**	containers	Load and discharge data
	Load size BARGES	**40**	containers	Load and discharge data
	Mooring time MAINS	45	minutes	ECT experts
	Mooring time BARGES	20	minutes	ECT experts
Tanking	# Tanking stations	2	-	Practice
Tanking	Tanking time	7.5	minutes	ECT experts
	Maximum fuel load per AGV	1200	liters	ECT experts
	Absolute minimum fuel load	20	liters	-

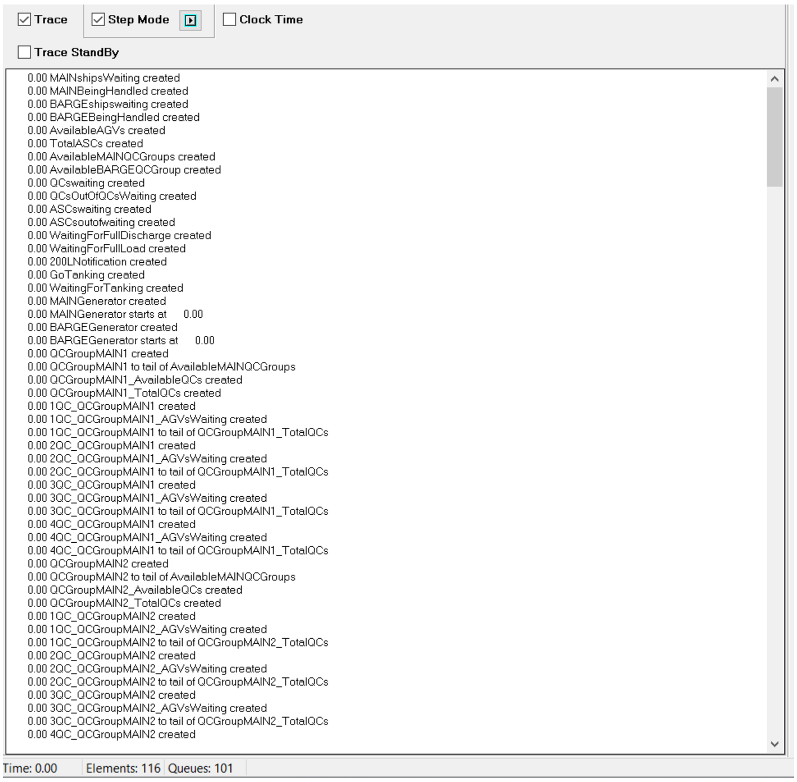
behave over simulation time. For a full transport cycle, that is from requesting an AGV by a QC or ASC until making this AGV available again by respectively an ASC or QC, the events have been traced accordingly.

When a ship is created, the PDL of the ShipGenerator states that this ship must always enter either the *MAINShipsWaiting* or *BARGEShipsWaiting* queue, after which the ship is picked from this queue - if first waiting in line - by the QCGroup and is allowed to moor. For MAINS, the mooring time is set at 45 minutes, according to ECT experts; BARGES moor with an average duration of 20 minutes. Therefore, the QCGroup has to hold the mooring ship for either 45 or 20 minutes, after which the QCGroup's QCs are activated to start discharging the ship. Figure F.12 shows this procedure in the TOMAS Trace view; indeed, the above mentioned steps are carried out by the simulator.

Once a ship has moored, the QCs are activated and start requesting an available AGV from the *AvailableAGVs* queue. If an AGV activates and starts to drive to the corresponding QC, the QC suspends until it wakes up again by the AGV once arrived at the QC TP. In Figure F.12 this is observed for the BARGE QC Group which's QCs, *1QCQCGroupBARGE* and *2QCQCGroupBARGE* are activated after 20 minutes, after which AGVs 1 and 2 leave the *AvailableAGVs* queue and start holding the precalculated driving time to the ship in minutes. These driving times correspond to the calculations: as AGVs are initially spawned in the center of the terminal, at y=500m and x=50m, and *1QCQCGroupBARGE* has y=515m and x=100m and *2QCQCGroupBARGE* has y=490m and x=100m, the driving times are respectively (abs(500-515)+abs(50-100))/2.76 = 23 seconds or 0.39 minutes and (abs(500-490)+abs(50-100))/2.76 = 22 seconds or 0.36 minutes, which is in accordance to the values being holded by AGVs 1 and 2 respectively. After arrival at the QC by the AGV, *1QCQCGroupBARGE* wakes up and starts to hold for 2 minutes handling time, according to the value in Table F.1 for QC handling time. Once *2QCQCGroupBARGE* has finished its first container, a second container is selected from the ship, after which AGV3 is requested from *AvailableAGVs*; AGV2 continues its journey to the destination ASC. Note that no discharge plans are considered; all QCs are able to 'reach' all containers on the ship. The TOMAS Trace view of this paragraph's procedure is depicted in Figure F.13.

Now e.g. AGV2 starts to move from *2QCQCGroupBARGE* to ASC9, with y=360m and x=0m, the driving time should be equal to (abs(490-360)+abs(100-0))/2.76 = 83 seconds or 1.38 minutes. This complies to the driving time of AGV2, which started its loaded trip at 22.36 and ended at ASC9 at 23.74 minutes. At arrival, AGV2 enters ASC9's *AGVsWaiting* queue, after which ASC9 is activated. Subsequently, ASC9 starts to handle AGV2 with a handling time that is equal to **half of the total ASC handling time**. This is very important to address: as was observed from practice that ASCs most of the time already are waiting for the AGV at the TP before the AGV's arrival, approximately half of the handling time is left for the AGV to wait at the TP for unloading its discharge container. After this handling time, AGV2 becomes available and enters *AvailableAGVs*, whereafter it starts to drive to an available buffer place at an ASC TP. Figure F.14 shows the TOMAS Trace view of this procedure.

Now it is checked whether the interactions are modeled correctly. First, the situation in which an AGV be-



```
0.00 MAINshipsWaiting created
0.00 MAINBeingHandled created
0.00 BARGEshipswaiting created
0.00 BARGEBeingHandled created
0.00 AvailableAGVs created
0.00 TotalASCs created
0.00 AvailableMAINQCGroups created
0.00 AvailableBARGEQCGroup created
0.00 QCswaiting created
0.00 QCsOutOfQCsWaiting created
0.00 ASCswaiting created
0.00 ASCsoutofwaiting created
0.00 WaitingForFullDischarge created
0.00 WaitingForFullLoad created
0.00 200LNotification created
0.00 GoTanking created
0.00 WaitingForTanking created
0.00 MAINGenerator created
0.00 MAINGenerator starts at      0.00
0.00 BARGEGenerator created
0.00 BARGEGenerator starts at      0.00
0.00 QCGroupMAIN1 created
0.00 QCGroupMAIN1 to tail of AvailableMAINQCGroups
0.00 QCGroupMAIN1_AvailableQCs created
0.00 QCGroupMAIN1_TotalQCs created
0.00 1QC_QCGroupMAIN1 created
0.00 1QC_QCGroupMAIN1_AGVsWaiting created
0.00 1QC_QCGroupMAIN1 to tail of QCGroupMAIN1_TotalQCs
0.00 2QC_QCGroupMAIN1 created
0.00 2QC_QCGroupMAIN1_AGVsWaiting created
0.00 2QC_QCGroupMAIN1 to tail of QCGroupMAIN1_TotalQCs
0.00 3QC_QCGroupMAIN1 created
0.00 3QC_QCGroupMAIN1_AGVsWaiting created
0.00 3QC_QCGroupMAIN1 to tail of QCGroupMAIN1_TotalQCs
0.00 4QC_QCGroupMAIN1 created
0.00 4QC_QCGroupMAIN1_AGVsWaiting created
0.00 4QC_QCGroupMAIN1 to tail of QCGroupMAIN1_TotalQCs
0.00 QCGroupMAIN2 created
0.00 QCGroupMAIN2 to tail of AvailableMAINQCGroups
0.00 QCGroupMAIN2_AvailableQCs created
0.00 QCGroupMAIN2_TotalQCs created
0.00 1QC_QCGroupMAIN2 created
0.00 1QC_QCGroupMAIN2_AGVsWaiting created
0.00 1QC_QCGroupMAIN2 to tail of QCGroupMAIN2_TotalQCs
0.00 2QC_QCGroupMAIN2 created
0.00 2QC_QCGroupMAIN2_AGVsWaiting created
0.00 2QC_QCGroupMAIN2 to tail of QCGroupMAIN2_TotalQCs
0.00 3QC_QCGroupMAIN2 created
0.00 3QC_QCGroupMAIN2_AGVsWaiting created
0.00 3QC_QCGroupMAIN2 to tail of QCGroupMAIN2_TotalQCs
0.00 4QC_QCGroupMAIN2 created
```

Time: 0.00 | Elements: 116 | Queues: 101

Figure F.11: TOMAS Trace view of the initialization procedure

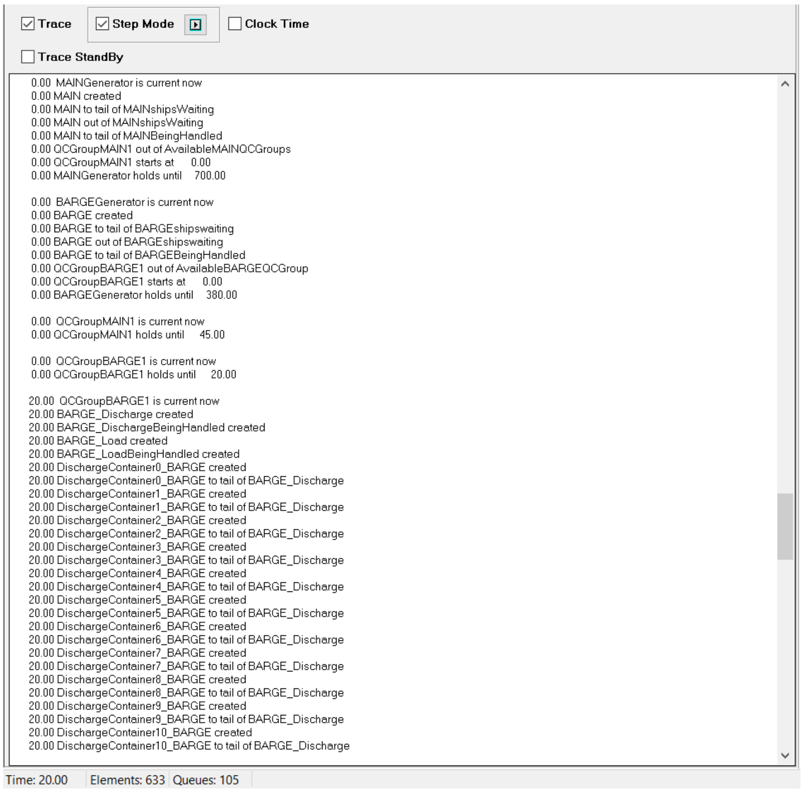
comes available and has to choose to go to either a waiting QC or waiting ASC is checked. According to the defined priority rule, QCs get priority over ASCs in assigning available AGVs. Figure F.15 shows the situation in which this is indeed the case. AGV40 becomes available after handling a loading container, whereafter *3QC-QCGroupMAIN1* leaves the *QCsWaiting* queue and enters a fictive queue, called *QCsOutOfWaiting*, which has been created to **ensure** that QCs which just leave the *QCsWaiting* queue also get assigned their corresponding AGV, which has just become available. Whenever this queue is larger than zero, all other processes are in standby mode to let the QC leaving this queue pick the available AGV. As can be seen, *3QCQCGroupMAIN1* picks AGV40, while *ASCsWaiting's* queue length is equal to 23.

Finally, next to QCs and ASCs waiting for AGVs it is checked whether AGVs go tanking according to the logic visualized in Figure 5.16. If an AGV's fuel load has dropped below 200 liters while the summed queue lengths of *GoTanking* and *WaitingForTanking* are at most 1, it is decided by either a QC or ASC to let the AGV drive to a tanking station by entering the queue *GoTanking*. Looking at Figures F.16, F.17 and F.18, this is indeed the case: as can be seen from the queue data, the queue lengths of *GoTanking* and *WaitingForTanking* are at most 2, which means that either of the two queues' lengths are at most 2, never both at the same time. AGV15 was thus allowed to enter the queue *GoTanking*. When AGV15 has arrived at the tanking station (see Figure F.17) the AGV enters the *WaitingForTanking* queue after which it waits until the tanking AGV drives away. Subsequently, AGV15 leaves the *WaitingForTanking* queue and is being holded for 5-10 minutes by the tanking station, after which AGV15 becomes available by entering *AvailableAGVs*.

From hand tracing the most important events, it is concluded that the developed diesel TOMAS model works according to the PDL specifications described in section 5.2.2.

F.3.2. Seed independence test

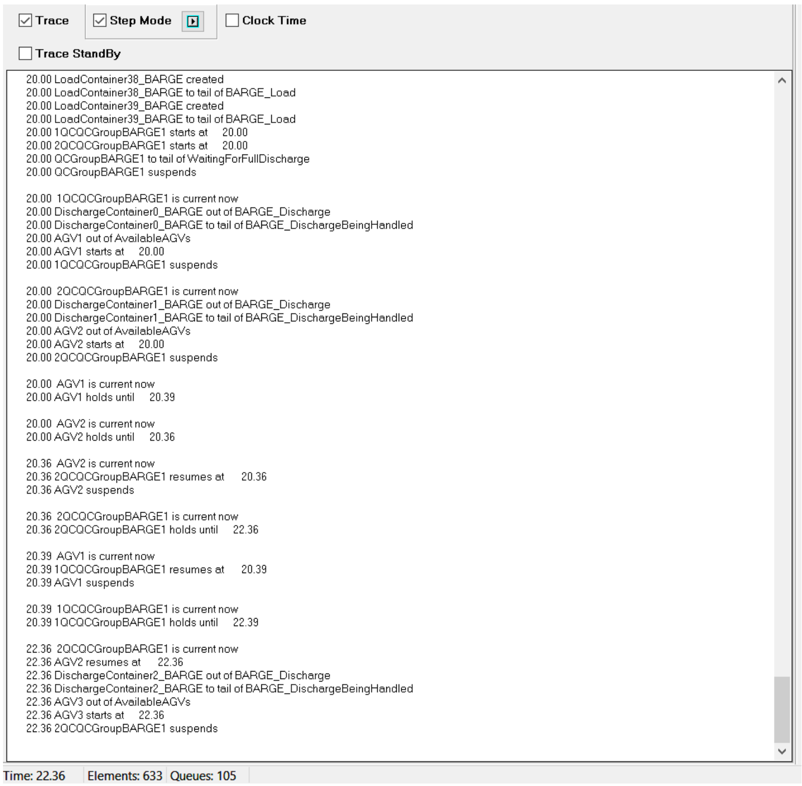
For every distribution depicted in Table 5.3 seeds are used which form a starting value for sampling from the created distribution. Changing these seeds should not lead to substantial differences in simulation outcomes, therefore it is tested whether different seeds grossly result in similar KPI values. Table F.2 shows the distributions present in the simulation model with the corresponding seed inputs. Five tests have been performed; the results can be retrieved from Table F.3. It is observed that changing seeds leads to minor differences in



```
 0.00  MAINGenerator is current now
 0.00 MAIN created
 0.00 MAIN to tail of MAINshipsWaiting
 0.00 MAIN out of MAINshipsWaiting
 0.00 MAIN to tail of MAINBeingHandled
 0.00 QCGroupMAIN1 out of AvailableMAINQCGroups
 0.00 QCGroupMAIN1 starts at     0.00
 0.00 MAINGenerator holds until    700.00

 0.00  BARGEGenerator is current now
 0.00 BARGE created
 0.00 BARGE to tail of BARGEshipswaiting
 0.00 BARGE out of BARGEshipswaiting
 0.00 BARGE to tail of BARGEBeingHandled
 0.00 QCGroupBARGE1 out of AvailableBARGEQCGroup
 0.00 QCGroupBARGE1 starts at     0.00
 0.00 BARGEGenerator holds until    380.00

 0.00  QCGroupMAIN1 is current now
 0.00 QCGroupMAIN1 holds until     45.00

 0.00  QCGroupBARGE1 is current now
 0.00 QCGroupBARGE1 holds until     20.00

20.00  QCGroupBARGE1 is current now
20.00 BARGE_Discharge created
20.00 BARGE_DischargeBeingHandled created
20.00 BARGE_Load created
20.00 BARGE_LoadBeingHandled created
20.00 DischargeContainer0_BARGE created
20.00 DischargeContainer0_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer1_BARGE created
20.00 DischargeContainer1_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer2_BARGE created
20.00 DischargeContainer2_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer3_BARGE created
20.00 DischargeContainer3_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer4_BARGE created
20.00 DischargeContainer4_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer5_BARGE created
20.00 DischargeContainer5_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer6_BARGE created
20.00 DischargeContainer6_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer7_BARGE created
20.00 DischargeContainer7_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer8_BARGE created
20.00 DischargeContainer8_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer9_BARGE created
20.00 DischargeContainer9_BARGE to tail of BARGE_Discharge
20.00 DischargeContainer10_BARGE created
20.00 DischargeContainer10_BARGE to tail of BARGE_Discharge
```

```
Time: 20.00    Elements: 633  Queues: 105
```

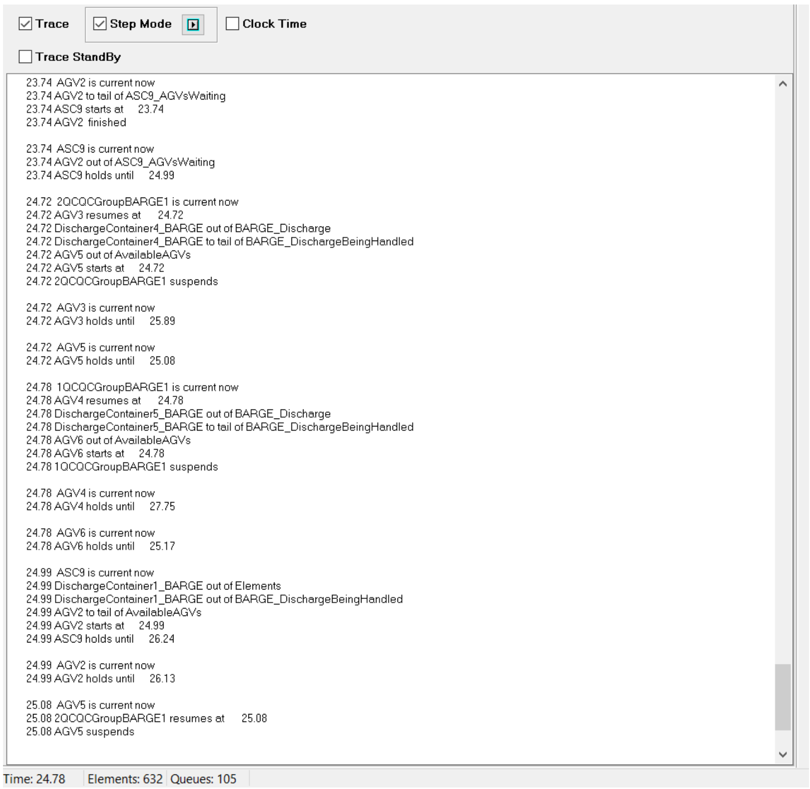
Figure F.12: TOMAS Trace view of creation and mooring of a MAIN and BARGE. After 20 minutes, Discharge containers are generated which are ready for discharge by BARGE QCs.



```
20.00 LoadContainer38_BARGE created
20.00 LoadContainer38_BARGE to tail of BARGE_Load
20.00 LoadContainer39_BARGE created
20.00 LoadContainer39_BARGE to tail of BARGE_Load
20.00 1QCQCGroupBARGE1 starts at     20.00
20.00 2QCQCGroupBARGE1 starts at     20.00
20.00 QCGroupBARGE1 to tail of WaitingForFullDischarge
20.00 QCGroupBARGE1 suspends

20.00  1QCQCGroupBARGE1 is current now
20.00 DischargeContainer0_BARGE out of BARGE_Discharge
20.00 DischargeContainer0_BARGE to tail of BARGE_DischargeBeingHandled
20.00 AGV1 out of AvailableAGVs
20.00 AGV1 starts at     20.00
20.00 1QCQCGroupBARGE1 suspends

20.00  2QCQCGroupBARGE1 is current now
20.00 DischargeContainer1_BARGE out of BARGE_Discharge
20.00 DischargeContainer1_BARGE to tail of BARGE_DischargeBeingHandled
20.00 AGV2 out of AvailableAGVs
20.00 AGV2 starts at     20.00
20.00 2QCQCGroupBARGE1 suspends

20.00  AGV1 is current now
20.00 AGV1 holds until     20.39

20.00  AGV2 is current now
20.00 AGV2 holds until     20.36

20.36  AGV2 is current now
20.36 2QCQCGroupBARGE1 resumes at     20.36
20.36 AGV2 suspends

20.36  2QCQCGroupBARGE1 is current now
20.36 2QCQCGroupBARGE1 holds until     22.36

20.39  AGV1 is current now
20.39 1QCQCGroupBARGE1 resumes at     20.39
20.39 AGV1 suspends

20.39  1QCQCGroupBARGE1 is current now
20.39 1QCQCGroupBARGE1 holds until     22.39

22.36  2QCQCGroupBARGE1 is current now
22.36 AGV2 resumes at     22.36
22.36 DischargeContainer2_BARGE out of BARGE_Discharge
22.36 DischargeContainer2_BARGE to tail of BARGE_DischargeBeingHandled
22.36 AGV3 out of AvailableAGVs
22.36 AGV3 starts at     22.36
22.36 2QCQCGroupBARGE1 suspends
```

```
Time: 22.36    Elements: 633  Queues: 105
```

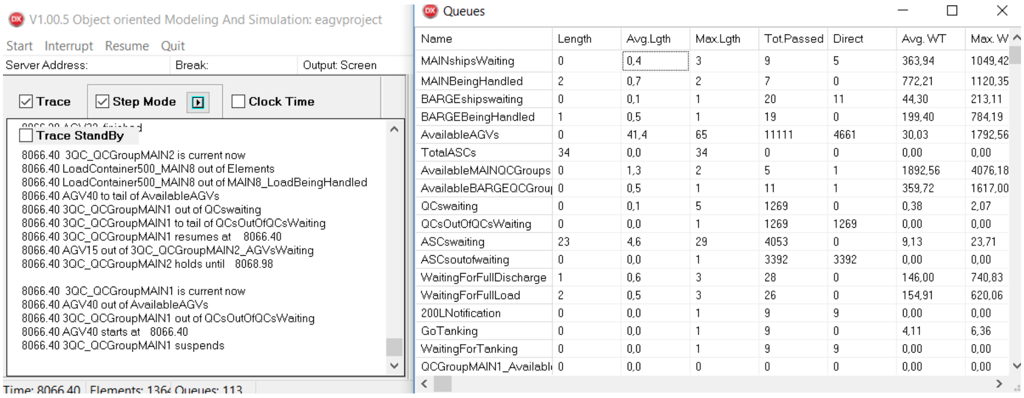
Figure F.13: TOMAS Trace view of the request of an AGV by a QC and its handling of a discharge container



```
23.74  AGV2 is current now
23.74 AGV2 to tail of ASC9_AGVsWaiting
23.74 ASC9 starts at     23.74
23.74 AGV2  finished

23.74  ASC9 is current now
23.74 AGV2 out of ASC9_AGVsWaiting
23.74 ASC9 holds until     24.99

24.72  2QCQCGroupBARGE1 is current now
24.72 AGV3 resumes at      24.72
24.72 DischargeContainer4_BARGE out of BARGE_Discharge
24.72 DischargeContainer4_BARGE to tail of BARGE_DischargeBeingHandled
24.72 AGV5 out of AvailableAGVs
24.72 AGV5 starts at     24.72
24.72 2QCQCGroupBARGE1 suspends

24.72  AGV3 is current now
24.72 AGV3 holds until     25.89

24.72  AGV5 is current now
24.72 AGV5 holds until     25.08

24.78  1QCQCGroupBARGE1 is current now
24.78 AGV4 resumes at      24.78
24.78 DischargeContainer5_BARGE out of BARGE_Discharge
24.78 DischargeContainer5_BARGE to tail of BARGE_DischargeBeingHandled
24.78 AGV6 out of AvailableAGVs
24.78 AGV6 starts at     24.78
24.78 1QCQCGroupBARGE1 suspends

24.78  AGV4 is current now
24.78 AGV4 holds until     27.75

24.78  AGV6 is current now
24.78 AGV6 holds until     25.17

24.99  ASC9 is current now
24.99 DischargeContainer1_BARGE out of Elements
24.99 DischargeContainer1_BARGE out of BARGE_DischargeBeingHandled
24.99 AGV2 to tail of AvailableAGVs
24.99 AGV2 starts at     24.99
24.99 ASC9 holds until     26.24

24.99  AGV2 is current now
24.99 AGV2 holds until     26.13

25.08  AGV5 is current now
25.08 2QCQCGroupBARGE1 resumes at      25.08
25.08 AGV5 suspends
```

```
Time: 24.78    Elements: 632  Queues: 105
```

Figure F.14: TOMAS Trace view of handling of an AGV by an ASC. AGV2 enters ASC9's *AGVsWaiting* queue, after which ASC9 holds for a fixed 2.5/2 = 1.25 minutes (see Table F.1) and lets AGV2 enter *AvailableAGVs*. Finally, AGV2 starts to drive to an available buffer ASC TP.

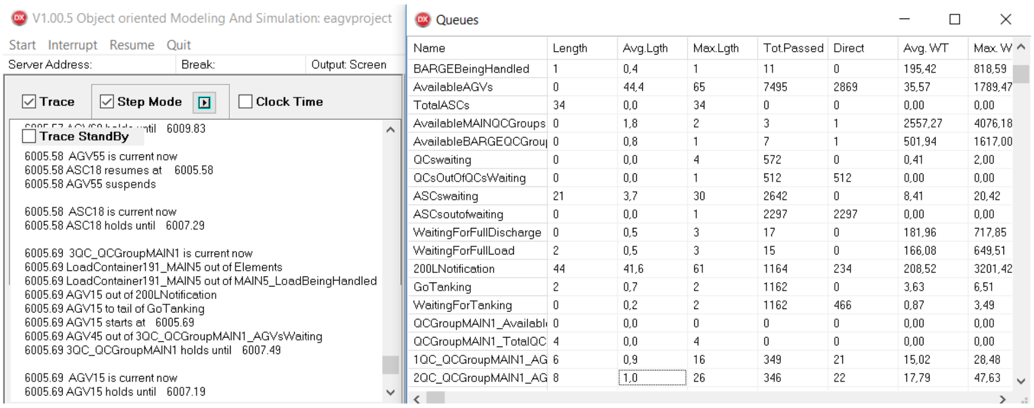


```
8066.40  3QC_QCGroupMAIN2 is current now
8066.40 LoadContainer500_MAIN8 out of Elements
8066.40 LoadContainer500_MAIN8 out of MAIN8_LoadBeingHandled
8066.40 AGV40 to tail of AvailableAGVs
8066.40 3QC_QCGroupMAIN1 out of QCswaiting
8066.40 3QC_QCGroupMAIN1 to tail of QCsOutOfQCsWaiting
8066.40 3QC_QCGroupMAIN1 resumes at    8066.40
8066.40 AGV15 out of 3QC_QCGroupMAIN2_AGVsWaiting
8066.40 3QC_QCGroupMAIN2 holds until    8068.98

8066.40  3QC_QCGroupMAIN1 is current now
8066.40 AGV40 out of AvailableAGVs
8066.40 3QC_QCGroupMAIN1 out of QCsOutOfQCsWaiting
8066.40 AGV40 starts at    8066.40
8066.40 3QC_QCGroupMAIN1 suspends
```

```
Time: 8066.40  Elements: 136  Queues: 113
```

Name	Length	Avg.Lgth	Max.Lgth	Tot.Passed	Direct	Avg. WT	Max. W
MAINshipsWaiting	0	0,4	3	9	5	363,94	1049,42
MAINBeingHandled	2	0,7	2	7	0	772,21	1120,35
BARGEshipswaiting	0	0,1	1	20	11	44,30	213,11
BARGEBeingHandled	1	0,5	1	19	0	199,40	784,19
AvailableAGVs	0	41,4	65	11111	4661	30,03	1792,56
TotalASCs	34	0,0	34	0	0	0,00	0,00
AvailableMAINQCGroups	0	1,3	2	5	1	1892,56	4076,18
AvailableBARGEQCGrou	0	0,5	1	11	1	359,72	1617,00
QCswaiting	0	0,1	5	1269	0	0,38	2,07
QCsOutOfQCsWaiting	0	0,0	1	1269	1269	0,00	0,00
ASCswaiting	23	4,6	29	4053	0	9,13	23,71
ASCsoutofwaiting	0	0,0	1	3392	3392	0,00	0,00
WaitingForFullDischarge	1	0,6	3	28	0	146,00	740,83
WaitingForFullLoad	2	0,5	3	26	0	154,91	620,06
200LNotification	0	0,0	1	9	9	0,00	0,00
GoTanking	0	0,0	1	9	0	4,11	6,36
WaitingForTanking	0	0,0	1	9	9	0,00	0,00
QCGroupMAIN1_Availabl	0	0,0	0	0	0	0,00	0,00

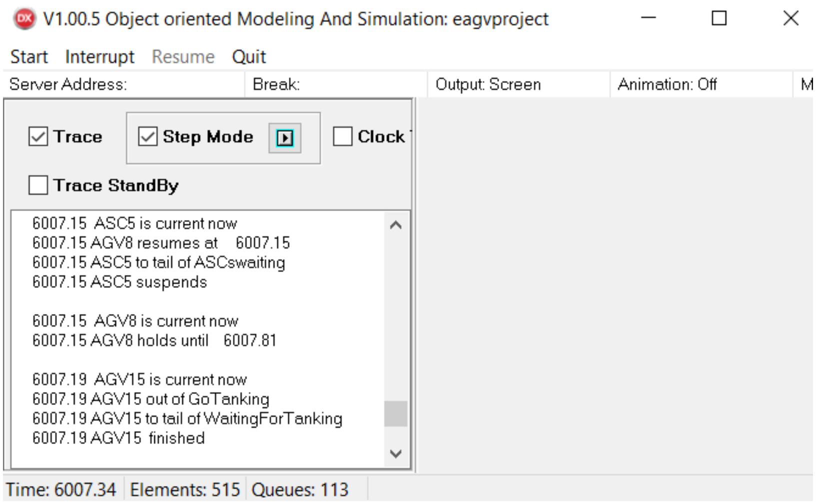
Figure F.15: TOMAS Trace view of the interaction between AGVs becoming available and QCs leaving *QcsWaiting* queue while there are also ASCs waiting for available AGVs



```
6005.58  AGV55 is current now
6005.58 ASC18 resumes at    6005.58
6005.58 AGV55 suspends

6005.58  ASC18 is current now
6005.58 ASC18 holds until    6007.29

6005.69  3QC_QCGroupMAIN1 is current now
6005.69 LoadContainer191_MAIN5 out of Elements
6005.69 LoadContainer191_MAIN5 out of MAIN5_LoadBeingHandled
6005.69 AGV15 out of 200LNotification
6005.69 AGV15 to tail of GoTanking
6005.69 AGV15 starts at    6005.69
6005.69 AGV45 out of 3QC_QCGroupMAIN1_AGVsWaiting
6005.69 3QC_QCGroupMAIN1 holds until    6007.49

6005.69  AGV15 is current now
6005.69 AGV15 holds until    6007.19
```

Name	Length	Avg.Lgth	Max.Lgth	Tot.Passed	Direct	Avg. WT	Max. W
BARGEBeingHandled	1	0,4	1	11	0	195,42	818,59
AvailableAGVs	0	44,4	65	7495	2869	35,57	1789,47
TotalASCs	34	0,0	34	0	0	0,00	0,00
AvailableMAINQCGroups	0	1,8	2	3	1	2557,27	4076,18
AvailableBARGEQCGrou	0	0,8	1	7	1	501,94	1617,00
QCswaiting	0	0,0	4	572	0	0,41	2,00
QCsOutOfQCsWaiting	0	0,0	1	512	512	0,00	0,00
ASCswaiting	21	3,7	30	2642	0	8,41	20,42
ASCsoutofwaiting	0	0,0	1	2297	2297	0,00	0,00
WaitingForFullDischarge	0	0,5	3	17	0	181,96	717,85
WaitingForFullLoad	2	0,5	3	15	0	166,08	649,51
200LNotification	44	41,6	61	1164	234	208,52	3201,42
GoTanking	2	0,7	2	1162	0	3,63	6,51
WaitingForTanking	0	0,2	2	1162	466	0,87	3,49
QCGroupMAIN1_Availabl	0	0,0	0	0	0	0,00	0,00
QCGroupMAIN1_TotalQC	4	0,0	4	0	0	0,00	0,00
1QC_QCGroupMAIN1_AG	6	0,9	16	349	21	15,02	28,48
2QC_QCGroupMAIN1_AG	8	1,0	26	346	22	17,79	47,63

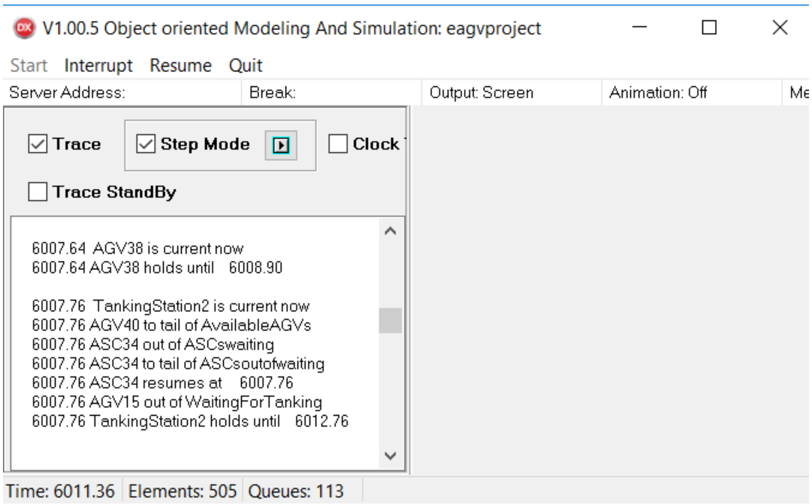
Figure F.16: TOMAS Trace view of the tanking logic of AGVs. AGV15 has received a 200 liters notification for refueling and the summed queue lengths of *GoTanking* and *WaitingForTanking* are at most 1, thus AGV15 goes tanking after handling a container. Note that the summed queue lengths are now 2 as AGV15 entered the *GoTanking* queue.



```
6007.15  ASC5 is current now
6007.15 AGV8 resumes at    6007.15
6007.15 ASC5 to tail of ASCswaiting
6007.15 ASC5 suspends

6007.15  AGV8 is current now
6007.15 AGV8 holds until    6007.81

6007.19  AGV15 is current now
6007.19 AGV15 out of GoTanking
6007.19 AGV15 to tail of WaitingForTanking
6007.19 AGV15  finished
```

Time: 6007.34 Elements: 515 Queues: 113

Figure F.17: TOMAS Trace view of AGV15 leaving the *GoTanking* queue and entering a tanking station's *WaitingForTanking* queue



```
6007.64  AGV38 is current now
6007.64 AGV38 holds until    6008.90

6007.76  TankingStation2 is current now
6007.76 AGV40 to tail of AvailableAGVs
6007.76 ASC34 out of ASCswaiting
6007.76 ASC34 to tail of ASCsoutofwaiting
6007.76 ASC34 resumes at    6007.76
6007.76 AGV15 out of WaitingForTanking
6007.76 TankingStation2 holds until    6012.76
```

Time: 6011.36 Elements: 505 Queues: 113

Figure F.18: TOMAS Trace view of a tanking station tanking AGV15 by holding it for an mount of time (5-10 minutes)

Table F.2: Seed independence tests using random seed input

	IAT MAIN	IAT BARGE	Handling time QC	Handling time ASC	Discharge MAIN	Load MAIN	Discharge BARGE	Load BARGE
Test 1	378	2097	503	359	82642	10	92655	264
Test 2	1777	32111	98364	2475	6301	1	80	9456
Test 3	83475	45324	2385	7	11111	12345	93465	87234
Test 4	3217	23947	34324	9867	5245	78642	8764	22222
Test 5	83657	3	90	2648	45789	8234	32452	33

Table F.3: Results seed independence tests

Output / test	1	2	3	4	5	Range relative to average [%]
Turnaround time MAIN [min]	856	850	846	852	855	1.16
Turnaround time BARGE [min]	230	250	226	238	234	5.04
QC productivity [mvs/hour/QC]	22.97	22.09	23.05	22.66	22.90	4.09
QC utilization rate [%]	76.5	73.7	76.8	76.2	76.8	4.05
AGV utilization rate [%]	79.7	76.3	79.8	78.8	79.3	4.36
Percentage of QCs waiting for AGVs [%]	26.4	28.9	23.7	25.0	26.7	19.70
Average waiting time QCs for AGVs [s]	123	123	123	122	123	0.81
Empty AGV trip fraction [%]	43.6	43.4	43.9	43.2	43.4	1.60

KPI outcomes, except from the *percentage of QCs waiting for AGVs*. Here, the range comprises 19.7% of the average value: possible reason for this large variety in values is the randomness with which AGVs become available after which a QC requests one. Even if AGVs become available 0.0001 seconds after a QC requests an AGV, this will count as *too late* which sounds unfair from a logistical perspective; when looking at the other KPI values, however, it can be seen that all test outcomes are robust, i.e. little fluctuation, therefore it is concluded that the developed simulation model is not heavily influenced by the seeds chosen.

F.3.3. Comparison with analytical derivations

Using back-of-the-envelope calculations instead of solely relying upon the simulation model is particularly useful for verification purposes. Therefore, the following calculations have been performed and subsequently compared with simulation outcomes; note that the inputs as described in Table F.1 are used in both the calculations and simulation.

A MAIN's and BARGE's time until full discharge can be calculated using both the handling time of a QC and the average travel time of an AGV to the QC. Before studying the KPI outcomes, it was checked with simulation what the average travel time of AGVs was: 1.75 minutes. This was confirmed by ECT data stating an average travel time of 2.10 minutes. As the QC process is modeled such that this travel time is subtracted from the total QC handling time with a minimum of 15 seconds - this is more realistic as crane operators are already hoisting a container from the ship before AGV arrival on the TP, after arrival the hoisted container only has to be put on the AGV - the average time it takes to handle one container by a single QC is approximately equal to 2 minutes. Having four QCs for a MAIN ship, the amount of containers that can be discharged per hour is (60/2)*4 = 120 containers. Consequently, for 500 discharge containers it takes 500/120 = 4.16 hours or 250 minutes for a full discharge; this is exactly equal to the simulation outcome. For loading a ship, no calculations can be performed as this is dependent on too many factors such as the waiting time of an AGV at the ASC before its container is loaded on top and the waiting time at the QC TP for container unloading.

However, an indication can be given as the QC productivity must be lower than 60/2 minutes QC handling = 30 moves/hour/QC. The actual number of moves must be lower as after a full discharge the QCs do not handle any containers until the first AGV arrives at the QC with a loading container on top. As all AGVs arrive randomly at their destination QCs, the actual productivity is per definition lower than the theoretical productivity (30 moves/hour/QC). When looking at the results in Table F.3, the productivity fluctuates around 22-23 moves/hour/QC, which is in accordance with intuition.

F.4. Statistical validation of the diesel AGV simulation model

Section 5.6 relatively compared the simulation outcomes with actual KPI values; this section tests whether the KPIs which were obtained by analyzing data - i.e. turnaround times, QC-AGV interaction and empty AGV trip fraction - are statistically valid by comparing the means of the simulation outcome and real value. For this means, the test statistic t_0 has been calculated with the formula (Gunes, n.d.):

$$t_0 = \frac{\mu_{simulation} - \mu_{real}}{\sigma / \sqrt{n}} \tag{F.1}$$

in which $\mu_{simulation}$ reflects the simulation outcome's mean, μ_{real} the real value's mean, σ the standard deviation of the sample and n the sample size. By replicating three times, the standard deviation of the MAIN turnaround time is 0.45, the standard deviation of the BARGE turnaround time is 0.33, the standard deviation of the percentage of QCs waiting for AGVs is 2.60 and the standard deviation of the empty AGV trip fraction is 0.25. Consequently, the t-statistics are as shown in Table F.4; it is observed that the turnaround times of MAIN ships and the percentage of QCs waiting for AGVs are not statistically valid while the other two KPIs *are* statistically validated. However, this does not necessarily mean that the developed model is 'wrong': several possibilities exist which may cause the inaccuracy, of which a few have been mentioned in section 5.6. As the simulation model's purpose is to compare a base scenario (i.e. diesel AGVs) with an alternative scenario (i.e. battery-electric AGVs), the model's structure and logic, which have been successfully verified, is considered more important than the level of accuracy. For this purpose, the simulation model is considered validated.

Table F.4: Results statistical comparison of means of simulation and reality with $\alpha = 0.05$ and $t_{critical} = 4.3$

	Simulation mean	**Real mean**	**T-statistic**	**T-statistic < critical t-statistic?**	**Statistically valid?**
Turnaround time MAIN [hours]	14.3	17.6	12.7	No	No
Turnaround time BARGE [hours]	3.8	3.3	2.6	Yes	Yes
Percentage of QCs waiting for AGVs [%]	26.3	16.8	6.3	No	No
Empty AGV trip fraction [%]	43.6	44.2	4.2	Yes	Yes

F.5. Verification of the battery-electric AGV simulation model

Likewise the diesel AGV simulation model, its battery-electric variant is verified with the techniques mentioned in section 5.6.

F.5.1. Hand event tracing

Instead of checking the correct working of the whole simulation model again, only the AGV request and handle procedures are traced. Figures F.19 to F.23 show the TOMAS Trace views of AGV11 from the moment it is assigned to a charging spot until being requested by a QC and leaving its charging spot. Figure F.19 shows AGV11 entering its selected quick charger's *GoCharging* queue, the global *GoCharging* queue, the global *PickACharger* queue - which is called *ChargingAGVs* in the PDL model - and the global *AGVsintoGoCharging* queue; recall that either QCs or ASCs perform these actions. The quick charger specific *GoCharging* queue is created for the sake of tracing purposes; as QCs and ASCs select a quick charger for an AGV being claimed by the least amount of other AGVs, a specific *GoCharging* queue gives insight in AGVs that have claimed this charging spot while not yet arrived. According to the AGV PDL, AGVs enter the global *GoCharging* queue too in order to perform the correct actions when executing the AGV procedure. In order to stay available for job requests, AGV11 also enters the global *ChargingAGVs* queue - in the simulation called *PickACharger*. Finally, to prevent errors during a simulation run, AGV11 also enters a global *AGVsintoGoCharging* queue: if a QC or ASC is planning to select AGV11 for a job, this queue prevents this selection from happening as all processes in the simulation are for that moment in standby mode, letting AGV11 indeed enter the global *GoCharging* queue and start its AGV procedure. This is observed in Figure F.19, where AGV11 immediately - that means it does not take any simulation time - leaves *AGVsintoGoCharging* again.

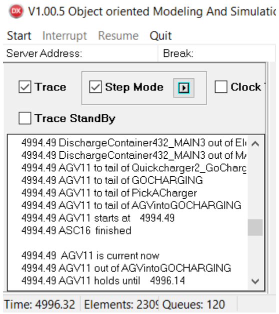
When arrived at QuickCharger2, AGV11 enters the quick charger's specific *WaitingForCharging* queue and stops its own procedure, as can be seen in Figure F.20. Apparently, another AGV is still charging at the charging spot and its battery level is not higher than 50%, otherwise the AGV would be stopped charging and AGV11 would enter the charging spot.

After almost 7 minutes of waiting, AGV11 starts charging, as observed in Figure F.21, by entering QuickCharger2's *ChargingAGV* queue (which' length can be maximally 1 as only one AGV can be charged at the same time).

Figure F.22 shows QuickCharger2's decision to further charge AGV11's battery, after reaching a certain battery level threshold (see Figure 5.23 for the defined thresholds). Apparently, either no QCs/ASCs were waiting for an available AGV or the battery level of AGV11 was not sufficient enough to leave the quick charger (>= 35% and >= 45 kWh as conditions). Since the input for this example simulation run comprised batteries with a capacity of 60 kWh - used in order to quickly find AGVs that must charge - apparently AGV11's battery level was sufficient for new jobs until charged to 80% of its battery level (0.8*60 = 48 kWh > 45 kWh threshold). Therefore, as Figure F.23 shows, AGV11 immediately leaves QuickCharger2 after charged until 80% and drives to *4QCQCGroupMAIN2*, which on its turn leaves the global *QCsWaiting* queue.

The final hand event trace is performed for a situation in which a QC or ASC requests an available AGV while *AvailableAGVs* is empty. Consequently, the QC/ASC needs to check *ChargingAGVs* to find for an available AGV with the highest battery level. Figure F.24 shows the implementation of this logic into the simulation: AGV55 is requested by *3QCQCGroupMAIN1* while it was charging at QuickCharger1. On its turn, AGV55 leaves QuickCharger1's specific *ChargingAGV* queue and starts to drive to *3QCQCGroupMAIN1*; subsequently, QuickCharger1 picks AGV39 for charging.

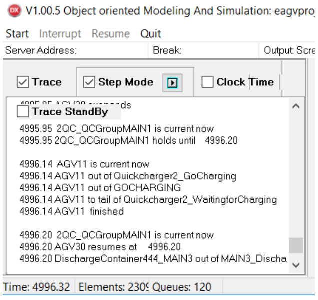
From the TOMAS Trace view, no irregularities appeared to show up during a simulation run; all events occur according to the PDL model specifications. However, from hand event tracing no insight is given in the charging times of the AGVs as well as the actual battery levels. A simple back-of-the-envelope calculation, though, can serve as an important verification point.



```
4994.49 DischargeContainer432_MAIN3 out of El
4994.49 DischargeContainer432_MAIN3 out of M
4994.49 AGV11 to tail of Quickcharger2_GoCharg
4994.49 AGV11 to tail of GOCHARGING
4994.49 AGV11 to tail of PickACharger
4994.49 AGV11 to tail of AGVintoGOCHARGING
4994.49 AGV11 starts at   4994.49
4994.49 ASC16  finished

4994.49  AGV11 is current now
4994.49 AGV11 out of AGVintoGOCHARGING
4994.49 AGV11 holds until   4996.14
```

Time: 4996.32 Elements: 230 Queues: 120

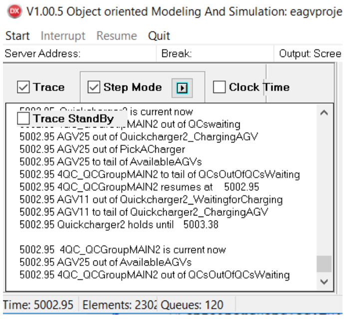
Figure F.19: TOMAS Trace view of AGV11 that starts driving to its selected charging spot called QuickCharger2



```
ds

4995.95  2QC_QCGroupMAIN1 is current now
4995.95 2QC_QCGroupMAIN1 holds until   4996.20

4996.14  AGV11 is current now
4996.14 AGV11 out of Quickcharger2_GoCharging
4996.14 AGV11 out of GOCHARGING
4996.14 AGV11 to tail of Quickcharger2_WaitingforCharging
4996.14 AGV11  finished

4996.20  2QC_QCGroupMAIN1 is current now
4996.20 AGV30 resumes at   4996.20
4996.20 DischargeContainer444_MAIN3 out of MAIN3_Discha
```

Time: 4996.32 Elements: 230 Queues: 120

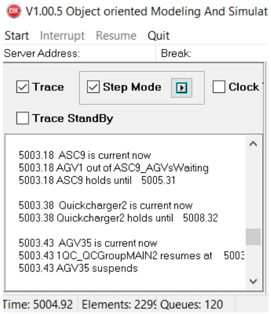
Figure F.20: TOMAS Trace view of AGV11 entering QuickCharger2's specific *WaitingForCharging* queue; it is observed that AGV11 indeed needs to wait for an AGV that is currently charging on this spot as time passes after entering the waiting queue without QuickCharger2 performing any actions for AGV11.



```
is current now
MAIN2 out of QCswaiting
5002.95 AGV25 out of Quickcharger2_ChargingAGV
5002.95 AGV25 out of PickACharger
5002.95 AGV25 to tail of AvailableAGVs
5002.95 4QC_QCGroupMAIN2 to tail of QCsOutOfQCsWaiting
5002.95 4QC_QCGroupMAIN2 resumes at   5002.95
5002.95 AGV11 out of Quickcharger2_WaitingforCharging
5002.95 AGV11 to tail of Quickcharger2_ChargingAGV
5002.95 Quickcharger2 holds until   5003.38

5002.95  4QC_QCGroupMAIN2 is current now
5002.95 AGV25 out of AvailableAGVs
5002.95 4QC_QCGroupMAIN2 out of QCsOutOfQCsWaiting
```

Time: 5002.95 Elements: 230 Queues: 120

Figure F.21: TOMAS Trace view of AGV11 starting with charging



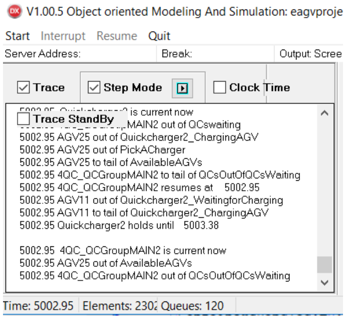
```
5003.18  ASC9 is current now
5003.18 AGV1 out of ASC9_AGVsWaiting
5003.18 ASC9 holds until   5005.31

5003.38  Quickcharger2 is current now
5003.38 Quickcharger2 holds until   5008.32

5003.43  AGV35 is current now
5003.43 1QC_QCGroupMAIN2 resumes at   500
5003.43 AGV35 suspends
```

Time: 5004.92 Elements: 229 Queues: 120

Figure F.22: TOMAS Trace view of AGV11 still being charged after reaching a certain battery level threshold

F.5.2. Comparison with analytical derivation

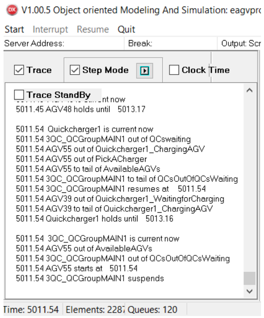
As AGVs are now not being tanked but opportunity charged, the charging times must be accurately verified. Suppose the following inputs: a battery capacity of 160 kWh, charging power of 300 kW and an efficiency rate of 97%. Consequently, a full charge time - that is from 0% to 100% battery level - would take, according to equation 5.2, ((0.8-0.0)*160/(300*0.97)) + ((1-0.8)*160/(0.25*300*0.97)) = 52.78 minutes. In TOMAS, checking whether maximum charging times are exceeding this maximum can be done by using the *Queues output win-*



```
                     is current now
                 MAIN2 out of QCswaiting
5002.95 AGV25 out of Quickcharger2_ChargingAGV
5002.95 AGV25 out of PickACharger
5002.95 AGV25 to tail of AvailableAGVs
5002.95 4QC_QCGroupMAIN2 to tail of QCsOutOfQCsWaiting
5002.95 4QC_QCGroupMAIN2 resumes at    5002.95
5002.95 AGV11 out of Quickcharger2_WaitingforCharging
5002.95 AGV11 to tail of Quickcharger2_ChargingAGV
5002.95 Quickcharger2 holds until    5003.38

5002.95  4QC_QCGroupMAIN2 is current now
5002.95 AGV25 out of AvailableAGVs
5002.95 4QC_QCGroupMAIN2 out of QCsOutOfQCsWaiting
```

```
Time: 5002.95 | Elements: 230 | Queues: 120
```

Figure F.23: TOMAS Trace view of AGV11 leaving QuickCharger2 after being requested by *4QCQCGroupMAIN2*; it is observed that AGV11 consequently leaves the global *PickACharger* queue - in PDL called *ChargingAGVs*.

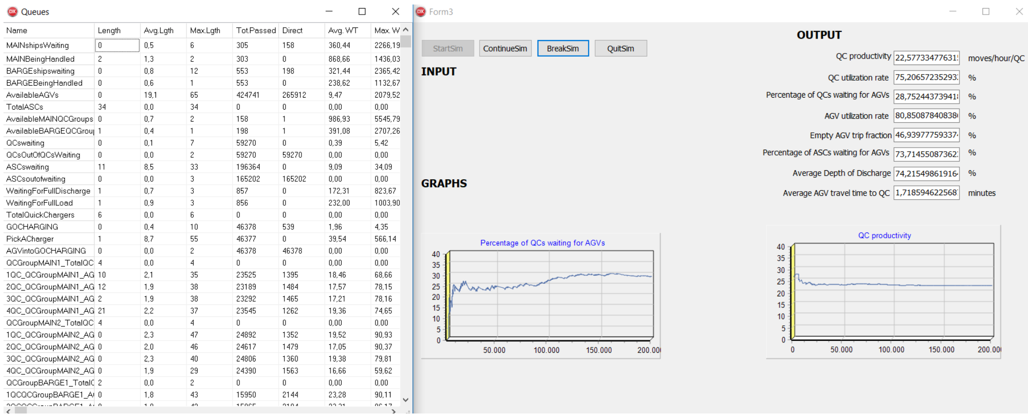


```
                     nt now
5011.45 AGV48 holds until    5013.17

5011.54  Quickcharger1 is current now
5011.54 3QC_QCGroupMAIN1 out of QCswaiting
5011.54 AGV55 out of Quickcharger1_ChargingAGV
5011.54 AGV55 out of PickACharger
5011.54 AGV55 to tail of AvailableAGVs
5011.54 3QC_QCGroupMAIN1 to tail of QCsOutOfQCsWaiting
5011.54 3QC_QCGroupMAIN1 resumes at    5011.54
5011.54 AGV39 out of Quickcharger1_WaitingforCharging
5011.54 AGV39 to tail of Quickcharger1_ChargingAGV
5011.54 Quickcharger1 holds until    5013.16

5011.54  3QC_QCGroupMAIN1 is current now
5011.54 AGV55 out of AvailableAGVs
5011.54 3QC_QCGroupMAIN1 out of QCsOutOfQCsWaiting
5011.54 AGV55 starts at    5011.54
5011.54 3QC_QCGroupMAIN1 suspends
```

```
Time: 5011.54 | Elements: 228 | Queues: 120
```

Figure F.24: TOMAS Trace view of AGV55 being requested by a QC while it was charging its battery; subsequently, AGV55 starts to drive to *3QCQCGroupMAIN1*.

dow. Figure F.25 shows this output for the inputs provided in this section by looking at the maximum Waiting Times (WT) of each QuickCharger's *ChargingAGV*, in which maximum one AGV is present for charging. The maximum waiting times are all smaller than 52.78 minutes which implies that the calculation model works according its specification.



Name	Length	Avg.Lgth	Max.Lgth	Tot.Passed	Direct	Avg. WT	Max. W
MAINshipsWaiting	0	0,5	6	305	158	360,44	2266,19
MAINBeingHandled	2	1,3	2	303	0	868,66	1436,03
BARGEshipswaiting	0	0,8	12	553	198	321,44	2365,42
BARGEBeingHandled	0	0,6	1	553	0	238,62	1132,67
AvailableAGVs	0	19,1	65	424741	265912	9,47	2079,52
TotalASCs	34	0,0	34	0	0	0,00	0,00
AvailableMAINQCGroups	0	0,7	2	158	1	986,93	5545,79
AvailableBARGEQCGrou	1	0,4	1	198	1	391,08	2707,26
QCswaiting	0	0,1	7	59270	0	0,39	5,42
QCsOutOfQCsWaiting	0	0,0	2	59270	59270	0,00	0,00
ASCswaiting	11	8,5	33	196364	0	9,09	34,09
ASCsoutofwaiting	0	0,0	3	165202	165202	0,00	0,00
WaitingForFullDischarge	1	0,7	3	857	0	172,31	823,67
WaitingForFullLoad	1	0,9	3	856	0	232,00	1003,90
TotalQuickChargers	6	0,0	6	0	0	0,00	0,00
GOCHARGING	0	0,4	10	46378	539	1,96	4,35
PickACharger	1	8,7	55	46377	0	39,54	566,14
AGVintoGOCHARGING	0	0,0	2	46378	46378	0,00	0,00
QCGroupMAIN1_TotalQC	4	0,0	4	0	0	0,00	0,00
1QC_QCGroupMAIN1_AG	10	2,1	35	23525	1395	18,46	68,66
2QC_QCGroupMAIN1_AG	12	1,9	38	23189	1484	17,57	78,15
3QC_QCGroupMAIN1_AG	2	1,9	38	23292	1465	17,21	78,16
4QC_QCGroupMAIN1_AG	21	2,2	37	23545	1262	19,36	74,65
QCGroupMAIN2_TotalQC	4	0,0	4	0	0	0,00	0,00
1QC_QCGroupMAIN2_AG	0	2,3	47	24892	1352	19,52	90,93
2QC_QCGroupMAIN2_AG	0	2,0	46	24617	1479	17,05	90,37
3QC_QCGroupMAIN2_AG	0	2,3	40	24806	1360	19,38	79,81
4QC_QCGroupMAIN2_AG	0	1,9	29	24390	1563	16,66	59,62
QCGroupBARGE1_Total	2	0,0	2	0	0	0,00	0,00
1QCQCGroupBARGE1_A	0	1,8	43	15950	2144	23,28	90,11

OUTPUT

QC productivity 22,57733477631 moves/hour/QC
QC utilization rate 75,20657235293 %
Percentage of QCs waiting for AGVs 28,75244373941 %
AGV utilization rate 80,85087840838 %
Empty AGV trip fraction 46,93977759337 %
Percentage of ASCs waiting for AGVs 73,71455087362 %
Average Depth of Discharge 74,21549861916 %
Average AGV travel time to QC 1,718594622568 minutes

Figure F.25: TOMAS Queues output window with the maximum charging times shown for every quick charger; when looking at all maximum Waiting Times (WT) of the quick chargers' *ChargingAGV* queue, it is observed that all these waiting times are smaller than 52.78 minutes, which means that the charging time calculation works according to equation 5.2

F.5.3. Seed independence test

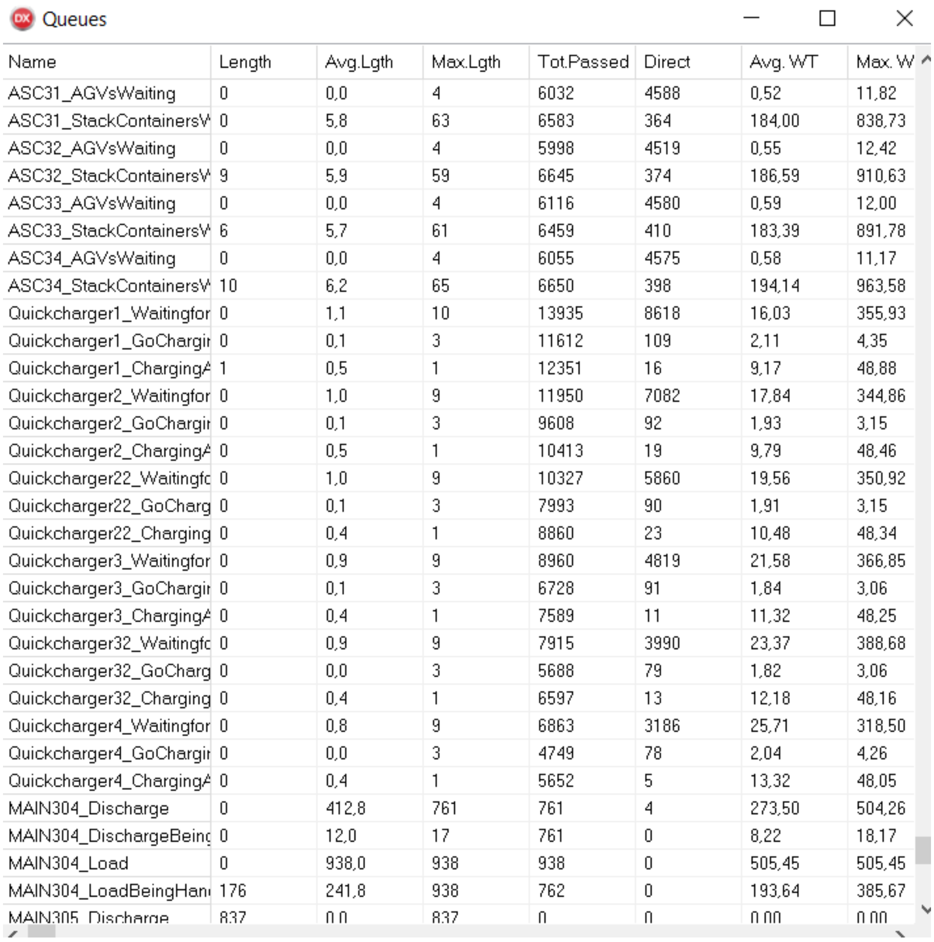
Likewise the diesel AGV simulation model, the battery-electric variant is verified by varying all distributions' seeds according to Table F.2. The results are shown in Table F.5; similar to the diesel variant, the battery-electric AGV simulation model does not appear to be sensitive to changes in seeds.

Table F.5: Results seed independence tests for the battery-electric AGV simulation model

Output / test	**1**	**2**	**3**	**4**	**5**	**Range relative to average [%]**
Turn around time MAIN [min]	866	864	855	864	865	1.40
Turn around time BARGE [min]	239	253	231	236	239	9.09
QC produtivity [mvs/hour/QC]	22.58	21.95	22.71	22.21	22.60	3.42
QC utilization rate [%]	75.2	73.2	75.7	73.6	75.5	3.36
AGV utilization rate [%]	80.6	78.3	80.9	79.7	80.9	1.49
Percentage of QCs waiting for AGVs [%]	28.8	31.3	26.4	28.5	26.9	17.07
Average waiting time QCs for AGVs [sec]	127	127	126	127	127	0.78
Empty AGV trip fraction	46.9	47.3	47.7	46.7	47.7	2.11

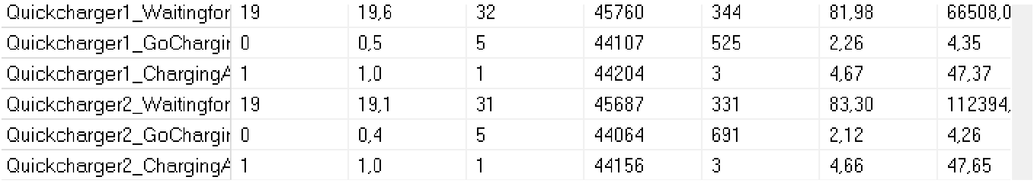
G

Charging and idle time outputs



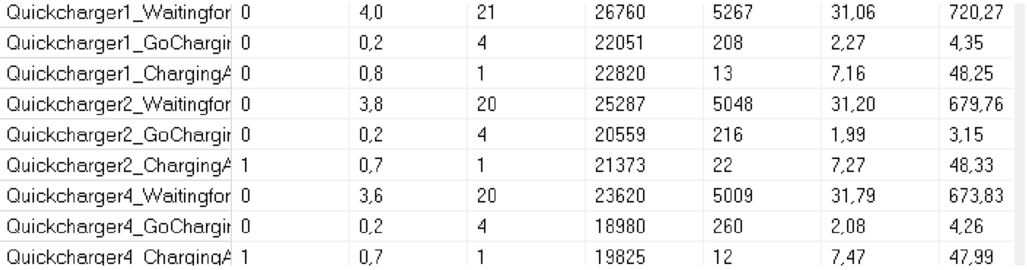
Name	Length	Avg.Lgth	Max.Lgth	Tot.Passed	Direct	Avg. WT	Max. W
ASC31_AGVsWaiting	0	0,0	4	6032	4588	0,52	11,82
ASC31_StackContainersV	0	5,8	63	6583	364	184,00	838,73
ASC32_AGVsWaiting	0	0,0	4	5998	4519	0,55	12,42
ASC32_StackContainersV	9	5,9	59	6645	374	186,59	910,63
ASC33_AGVsWaiting	0	0,0	4	6116	4580	0,59	12,00
ASC33_StackContainersV	6	5,7	61	6459	410	183,39	891,78
ASC34_AGVsWaiting	0	0,0	4	6055	4575	0,58	11,17
ASC34_StackContainersV	10	6,2	65	6650	398	194,14	963,58
Quickcharger1_Waitingfor	0	1,1	10	13935	8618	16,03	355,93
Quickcharger1_GoChargi	0	0,1	3	11612	109	2,11	4,35
Quickcharger1_Charging	1	0,5	1	12351	16	9,17	48,88
Quickcharger2_Waitingfor	0	1,0	9	11950	7082	17,84	344,86
Quickcharger2_GoChargi	0	0,1	3	9608	92	1,93	3,15
Quickcharger2_Charging	0	0,5	1	10413	19	9,79	48,46
Quickcharger22_Waitingf	0	1,0	9	10327	5860	19,56	350,92
Quickcharger22_GoCharg	0	0,1	3	7993	90	1,91	3,15
Quickcharger22_Charging	0	0,4	1	8860	23	10,48	48,34
Quickcharger3_Waitingfor	0	0,9	9	8960	4819	21,58	366,85
Quickcharger3_GoChargi	0	0,1	3	6728	91	1,84	3,06
Quickcharger3_Charging	0	0,4	1	7589	11	11,32	48,25
Quickcharger32_Waitingf	0	0,9	9	7915	3990	23,37	388,68
Quickcharger32_GoCharg	0	0,0	3	5688	79	1,82	3,06
Quickcharger32_Charging	0	0,4	1	6597	13	12,18	48,16
Quickcharger4_Waitingfor	0	0,8	9	6863	3186	25,71	318,50
Quickcharger4_GoChargi	0	0,0	3	4749	78	2,04	4,26
Quickcharger4_Charging	0	0,4	1	5652	5	13,32	48,05
MAIN304_Discharge	0	412,8	761	761	4	273,50	504,26
MAIN304_DischargeBein	0	12,0	17	761	0	8,22	18,17
MAIN304_Load	0	938,0	938	938	0	505,45	505,45
MAIN304_LoadBeingHan	176	241,8	938	762	0	193,64	385,67
MAIN305_Discharge	837	0,0	837	0	0	0,00	0,00

Figure G.1: TOMAS Queues output window of charging times, i.e. the Avg WT of an AGV in *QuickChargerChargingAGV*



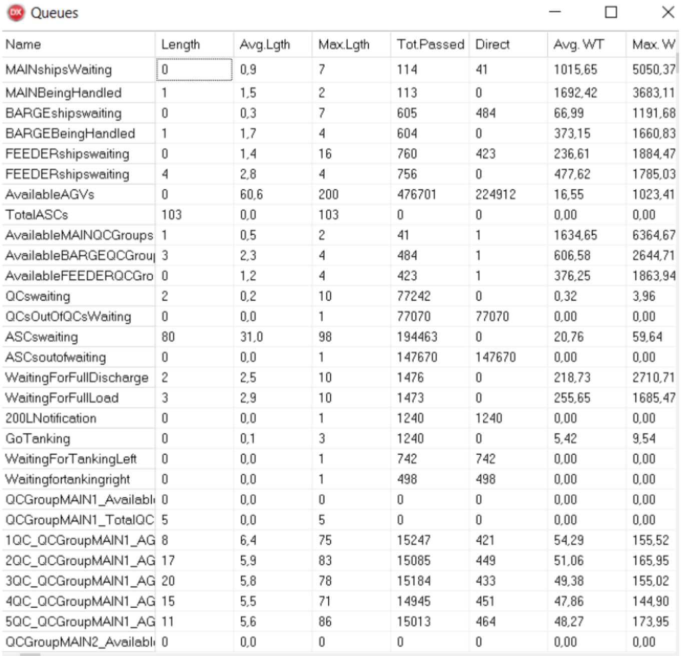
Quickcharger1_Waitingfor	19	19,6	32	45760	344	81,98	66508,0
Quickcharger1_GoChargir	0	0,5	5	44107	525	2,26	4,35
Quickcharger1_ChargingA	1	1,0	1	44204	3	4,67	47,37
Quickcharger2_Waitingfor	19	19,1	31	45687	331	83,30	112394,
Quickcharger2_GoChargir	0	0,4	5	44064	691	2,12	4,26
Quickcharger2_ChargingA	1	1,0	1	44156	3	4,66	47,65

Figure G.2: TOMAS Queues output window of charging times for 2 quick chargers installed on the DDN (4.67 minutes for QuickCharger1, 4.66 minutes for QuickCharger2)



Quickcharger1_Waitingfor	0	4,0	21	26760	5267	31,06	720,27
Quickcharger1_GoChargir	0	0,2	4	22051	208	2,27	4,35
Quickcharger1_ChargingA	0	0,8	1	22820	13	7,16	48,25
Quickcharger2_Waitingfor	0	3,8	20	25287	5048	31,20	679,76
Quickcharger2_GoChargir	0	0,2	4	20559	216	1,99	3,15
Quickcharger2_ChargingA	1	0,7	1	21373	22	7,27	48,33
Quickcharger4_Waitingfor	0	3,6	20	23620	5009	31,79	673,83
Quickcharger4_GoChargir	0	0,2	4	18980	260	2,08	4,26
Quickcharger4_ChargingA	1	0,7	1	19825	12	7,47	47,99

Figure G.3: TOMAS Queues output window of charging times for 3 quick chargers installed on the DDN



Name	Length	Avg.Lgth	Max.Lgth	Tot.Passed	Direct	Avg. WT	Max. W
MAINshipsWaiting	0	0,9	7	114	41	1015,65	5050,37
MAINBeingHandled	1	1,5	2	113	0	1692,42	3683,11
BARGEshipswaiting	0	0,3	7	605	484	66,99	1191,68
BARGEBeingHandled	1	1,7	4	604	0	373,15	1660,83
FEEDERshipswaiting	0	1,4	16	760	423	236,61	1884,47
FEEDERshipswaiting	4	2,8	4	756	0	477,62	1785,03
AvailableAGVs	0	60,6	200	476701	224912	16,55	1023,41
TotalASCs	103	0,0	103	0	0	0,00	0,00
AvailableMAINQCGroups	1	0,5	2	41	1	1634,65	6364,67
AvailableBARGEQCGrou	3	2,3	4	484	1	606,58	2644,71
AvailableFEEDERQCGro	0	1,2	4	423	1	376,25	1863,94
QCswaiting	2	0,2	10	77242	0	0,32	3,96
QCsOutOfQCsWaiting	0	0,0	1	77070	77070	0,00	0,00
ASCswaiting	80	31,0	98	194463	0	20,76	59,64
ASCsoutofwaiting	0	0,0	1	147670	147670	0,00	0,00
WaitingForFullDischarge	2	2,5	10	1476	0	218,73	2710,71
WaitingForFullLoad	3	2,9	10	1473	0	255,65	1685,47
200LNotification	0	0,0	1	1240	1240	0,00	0,00
GoTanking	0	0,1	3	1240	0	5,42	9,54
WaitingForTankingLeft	0	0,0	1	742	742	0,00	0,00
Waitingfortankingright	0	0,0	1	498	498	0,00	0,00
QCGroupMAIN1_Availabl	0	0,0	0	0	0	0,00	0,00
QCGroupMAIN1_TotalQC	5	0,0	5	0	0	0,00	0,00
1QC_QCGroupMAIN1_AG	8	6,4	75	15247	421	54,29	155,52
2QC_QCGroupMAIN1_AG	17	5,9	83	15085	449	51,06	165,95
3QC_QCGroupMAIN1_AG	20	5,8	78	15184	433	49,38	155,02
4QC_QCGroupMAIN1_AG	15	5,5	71	14945	451	47,86	144,90
5QC_QCGroupMAIN1_AG	11	5,6	86	15013	464	48,27	173,95
QCGroupMAIN2_Availabl	0	0,0	0	0	0	0,00	0,00

Figure G.4: TOMAS Queues output window of the diesel AGV base case for the DDE with the average AGV idle time in between two jobs defined as *Avg WT* in *AvailableAGVs* queue

H

Total costs of ownership calculations

In this Appendix, the calculations performed in order to obtain the total costs of ownership for the base case and scenario variants are explained in more detail. The reader is noted that the corresponding input values have already been discussed in section 7.2 and synthesized in Table 7.3; see Appendix J for the expert references.

H.1. Base cases

The total costs of ownership of a fully diesel and battery-electric AGV fleet for both the DDN and DDE have been calculated using the calculations as described in the following sections. For the cost elements distinguished in the remainder of these sections, the reader is referred to Table 7.4.

H.1.1. Pilot costs

Regarding the pilot costs for the DDN, once 50,000 euros is paid for assisting the tendered supplier of battery-electric AGVs in developing a prototype model. This value is obtained from ECT experts of the I&E Department. For the diesel AGV, no prototype costs are made as these are already operational at the Delta Terminal. For the DDE, no pilot costs are made as ECT is planning to start with the deployment of battery-electric AGVs at the DDN.

H.1.2. AGV purchase costs

For a fully diesel AGV fleet, 500,000 euros per AGV times 65 AGVs must be initially invested. This equals 32,500,000 euros for the DDN. For a fully battery-electric AGV fleet consisting of an equal amount of AGVs, also 32,500,000 euros must be paid initially, however, now the battery costs must be added to this value. Given 160 kWh batteries on a fleet size of 65 AGVs, 160 kWh times 600 euros/kWh times 65 AGVs equals 6,240,000 euros; the resulting AGV purchase costs equal 38,740,000 euros.
Considering the DDE, a vehicle fleet of 200 AGVs consequently adds up to 100,000,000 and 119,200,000 euros respectively.

H.1.3. Charging infrastructure costs

For the charging infrastructure costs, only the battery-electric base case is considered. Regarding the DDN, 1,750,000 euros plus 200,000 euros per charger times 6 chargers equals 3,050,000 euros. For the DDE, the 1,750,000 euros cost estimate given 6 chargers and 300 kW has been multiplied consequently with a factor 20/6 to scale the costs towards the DDE base case, i.e. 20 chargers installed along stack side. As a result, the total costs, including 200,000 euros per charger multiplied with 20 chargers, add up to 9,933,333 euros.

H.1.4. Implementation costs

The implementation costs consist of retraining maintenance employees, adjusting maintenance stations to battery-electric AGVs and developing a battery management communication system between AGVs and the TOS. Recalling from section 7.2, these costs add up to 190,000 euros, which must be taken into account for both the DDN and DDE as a communication system and service station must be developed at both sides of the Delta Terminal.

H.1.5. Fueling costs

For obtaining the fueling costs, the simulation outcomes have been used accordingly to obtain the amount of loaded and empty kilometers driven by AGVs per year. Looking at Table 7.2, it is shown that battery-electric AGVs drive on average 4.1% more kilometers when compared to their diesel counterpart which is due to the fact that more empty kilometers are driven for charging trips. For the DDN, 12,549 kilometers are driven per battery-electric AGV per year; a diesel AGV drives 12,060 kilometers on average per year. Accounting for the increased empty trip fraction, the loaded and empty kilometers driven per AGV per year are shown in Table H.1. For diesel AGVs at the DDN, the empty trip fraction is 43.6%; for battery-electric AGVs this fraction increased to 46.9%. Taking an empty diesel fuel consumption of 1.10 L/km and loaded consumption of 1.80 L/km, and taking an empty battery-electric fuel consumption of 4.33 kWh/km and loaded consumption of 7.09 kWh/km, the total fueling costs are calculated accordingly over 15 years using a default diesel price of 1.00 euros/L and a default electricity price of 0.07 euros/kWh. For example, for a fully battery-electric AGV fleet at the DDN, the total fueling costs over 15 years equal 65x(5885x15x4.33 + (12549-5885)x15x7.09)x0.07 = 4,984,993 euros.

The same calculations have been performed for the DDE, with a diesel empty AGV trip fraction of 43.9% and a battery-electric empty AGV trip fraction of 48%, both obtained from the simulation outcomes. Consequently, the total fueling costs for all base cases are obtained.

Table H.1: Calculation of fueling costs for the DDN and DDE base cases

	Diesel base case DDN	**Battery-electric base case DDN**	**Diesel base case DDE**	**Battery-electric base case DDE**
Total kilometers per AGV per year [km/AGV/year]	12,060	12,549	16,015	18,096
Of which empty kilometers per AGV per year [km/AGV/year]	5,258	5,885	7,031	8,686
Total diesel consumed per AGV per year [L/AGV/year]	18,027	-	23,906	-
Total electric energy consumed per AGV per year [kWh/AGV/year]	-	72,728	-	104,327
Total diesel consumed over all AGVs over 15 years [L]	17,659,250	-	71,716,772	-
Total electric energy consumed over all AGVs over 15 years [kWh]	-	71,214,186	-	312,981,177
Total fueling costs over 15 years [€]	**17,659,250**	**4,984,993**	**71,716,772**	**21,908,682**

H.1.6. AGV maintenance costs

Intuitively, a substantial decrease in AGV maintenance costs were to be expected when making the transition towards a fully battery-electric AGV fleet. However, when looking at Table 7.4 a relatively very small cost decrease is observed. For both the DDN and DDE, the maintenance costs decrease with around 1,000,000 euros on a total of 18,000,000 euros and 56,000,000 euros respectively. This is caused by the replacement costs of the AGV batteries within around 10 years, which almost fully compensate the savings on AGV maintenance. Taking the DDN diesel base case as an example, the total maintenance costs over 15 years equal (6 euros per running hour x 30,000 running hours per AGV x 65 AGVs) + (103,000 euros per AGV x 65 AGVs) = 18,392,400 euros. For a DDE battery-electric AGV fleet, the AGV maintenance costs over 15 years equal (6 euros per running hour x 30,000 running hours per AGV x 200 AGVs) + (96,000 euros per new battery x 200 AGVs) = 55,200,000 euros.

H.1.7. Refueling infrastructure maintenance costs

For the maintenance on refueling infrastructure, a distinction is made between petrol stations and chargers. The current maintenance on petrol stations equal 3,000 euros per year; over 15 years this equal 45,000 euros for both the DDN and DDE. For the maintenance on the chargers, 3% of the initial investments is annually spent on maintenance. Consequently, for the DDN the total maintenance costs over 15 years equal 0.03 x 200,000 euros per charger x 6 chargers x 15 years = 540,000 euros. For the DDE, maintenance costs count up to 0.03 x 200,000 euros x 20 chargers x 15 = 1,800,000 euros. It is assumed that no maintenance will be required on the underlying cabling infrastructure with 15 years.

H.1.8. Downtime costs

Most important cost element to incorporate in this study is the downtime costs as these equal 9,520 euros per hour delay in MAINS for the DDN and 11,900 euros per hour for the DDE. Looking at Table 7.4, it is observed that downtime costs take up a significant share in the total costs of ownership, especially for the DDE. The reader is reminded that these downtime costs reflect the delays in MAIN turnaround times compared to the diesel base case at both sides of the Delta Terminal. These values are calculated as follows: The delay in turnaround time of MAIN ships have been obtained from the simulation results. For the DDN, 11 minutes delay occur while at the DDE the delay in MAIN turnaround time for the base is much higher: 112 minutes. Subsequently, the downtime costs per ship are calculated by multiplying 11/60 with 9,529 euros/hour for the DDN and multiplying 112/60 with 11,900 euros/hour for the DDE. Finally, these values have to be multiplied with the number of MAINS mooring at both sides of the Delta Terminal per year whereafter these values must be multiplied with a 15 years time horizon. At the DDN, the number of MAINS mooring per year equal (1440 minutes per day x 365 days) / 700 = 750 MAINS, where 700 resembles the inter arrival time of MAIN ships in minutes. At the DDE, (1440 x 365) / 1093 = 480 MAINS berth per year along the quay wall.

Considering the DDN, the total downtime costs over 15 years equal 9,520 euros/hour x (11/60) hours delay/MAIN x 750 MAINS/year x 15 years = 19,635,000 euros. Regarding the DDE, the total downtime costs are 11,900 euros/hour x (112/60) hours delay/MAIN x 480 MAINS/year x 15 years = 159,936,000 euros. Both the outcomes take up a significant share in the total costs of ownership: for the DDN the delay costs are 25% of the TCO, for the DDE these downtime costs equal 45% of the total costs. What can thus be concluded is that preventing delays from occurring will result in a more beneficial TCO, even if this means that a lot more battery-electric AGVs and chargers must initially be purchased. Charging is considered a subprocess of the main process: handling vessels.

H.1.9. Disposal costs

As disposing a Li-Ion battery weighing 4 tons averagely costs 16,000 euros (see Table 7.3), the total disposal costs for the DDN equals 16,000 euros x 65 batteries = 1,040,000 euros. Regarding the DDE, the disposal costs are 16,000 euros x 200 batteries = 3,200,000 euros.

H.1.10. Incomes

Incomes are expected on subsidies attained from the government regarding EIA and WBSO. Taking 13.5% of the AGV purchase costs, 5,229,900 euros can be attained for the DDN side and 17,433,000 euros for the DDE. Regarding WBSO, 30% can be saved on pilot and maintenance education costs. Consequently, 27,000 and 12,000 euros can be saved (as pilot costs are only made at the DDN). Finally, the salvage values of AGVs and their batteries have been calculated by multiplying the number of AGVs and batteries initially purchased with the corresponding salvage value.

H.1.11. Total costs of ownership

Finally, the total costs of ownership have been calculated by summing the capital and operational expenditures. Incomes are subtracted from the operational expenditures.

I

Scope extension to DDE

I.1. Extending simulation with DDE

While the northern side of the Delta Terminal, the DDN, has a quay length of only 1 kilometer, the DDE is much larger with a quay length of over 3 kilometers. Consequently, a separate DDE version of both simulation model variants, diesel and electric, has been developed by changing the input parameters and adding an extra Ship Generator called *FEEDER Generator*. From load and discharge data obtained from ECT, it was observed that a significant share of the total ships mooring at the DDE were FEEDERS and, hence, this ship type was included in the simulation model. The adjusted input parameters for the DDE are depicted in Table I.1. As can be seen from the layout and operational parameters, the DDE covers a much wider area with 10 mooring spots instead of 3 at the DDN.

I.1.1. DDE model validation

Since much more containers are handled per time step at the DDE than at the DDN, simulation run time took considerably longer; for the base case scenario, 160,000 simulation time steps, i.e. minutes, or 111 days were simulated as all KPIs found out to be structurally stable at this point (compared to 210,000 time steps for the DDN). All KPIs turned out to be approximately equal to the DDN values, except from the turnaround times of the ships, which are depicted in Figure A.7 in Appendix A for the DDE. Table I.2 shows the comparison of the simulation outcomes with actual ECT KPI values. It is observed that the simulated values are very accurate with exception of the turnaround time of BARGES; the difference is almost 40% from the actual value. This can most likely be explained by the fact that the BARGE QC Groups are located at the edges of the quay wall (both between 2500-3000 meters and 0-1000 meters). Thereby, AGVs have to travel substantially longer to these ships which results in a higher turnaround time; the MAIN QC Groups e.g. are located at the center of the DDE (around 1500 meters), thereby their turnaround time is smaller than the actual value. In reality, smart planning by the TOS takes care of these long traveling distances, thereby the actual turnaround time of BARGES turns out to be smaller.

I.1.2. Simulation experiment results for the DDE

For the DDE, the same variables have been varied as for the DDN, except from the opportunity charge threshold: this variable is considered to have no/marginal effect on terminal performance and is therefore left out for the remainder of this study. What can be concluded, however, is that setting this threshold value at 70% instead of at 50% decreases the average DoD which is economically effective in terms of battery lifetime. The variables are varied over a different range than for the DDN as the DDE is much larger and has a larger fleet size; the base case and range are depicted in Table I.3.

Number of AGVs

Likewise the DDN, a convex curve is observed which becomes flatter at 75% of the current amount of AGVs driving on the DDE (see Figure I.1). However, where the DDN required 10 extra battery-electric AGVs - i.e. +23% - to be purchased in order to acquire an equal transport performance as with diesel AGVs, at the DDE almost 100 extra AGVs - i.e. +50% - are needed to obtain equal turnaround times of MAINS. This is explained by the larger distances that AGVs must cover for charging as well as the chosen base case configuration with

Table I.1: Simulation parameters adjusted for the DDE

	Parameter	Value	Unit	Obtained from
Topology	Size of terminal	3000 x 119	meters	Delta view
	# QCs per MAIN	5	-	QC data
	# QCs per BARGE	2	-	QC data
	# QCs per FEEDER	2	-	QC data
	# MAIN QC Groups	2	-	Delta view
	# BARGE QC Groups	4	-	Delta view
	# FEEDER QC Groups	4	-	Delta view
	Longitudinal distance QCs	50-75	meters	QC data
	# ASCs	103	-	Delta view
	Longitudinal distance ASCs	25	meters	Delta view
Operational	# AGVs	200	-	ECT experts
	Speed of AGV	2.76	meters/second	AGV and QC data
	Handling time QC	N(109,127), minimum 15	seconds	QC data
	Handling time ASC	N(151,32), minimum 60	seconds	ASC data
	Inter arrival time MAINS	Exp(1093)	minutes	Load and discharge data
	Inter arrival time BARGES	Exp(216)	minutes	Load and discharge data
	Inter arrival time FEEDERS	Exp(184)	minutes	Load and discharge data
	Discharge size MAINS	N(1211,1157), minimum 500, maximum 3000	containers	Load and discharge data
	Load size MAINS	N(1490,1255), minimum 500, maximum 2500	containers	Load and discharge data
	Discharge size BARGES	N(45,55), minimum 15, maximum 220	containers	Load and discharge data
	Load size BARGES	N(20,28), minimum 15, maximum 220	containers	Load and discharge data
	Discharge size FEEDERS	N(78,90), minimum 30, maximum 300	containers	Load and discharge data
	Load size FEEDERS	N(87,123), minimum 30, maximum 300	containers	Load and discharge data
Tanking	# Tanking stations	4	-	Practice
	Tanking time	7.5	minutes	ECT experts
	Maximum fuel load per AGV	1200	liters	ECT experts
	Absolute minimum fuel load	20	liters	-

20 chargers: as will be shown later, for the DDE a substantial larger amount of chargers is required to reduce the difference in turnaround times of MAINS to an acceptable level.

Battery capacity

Similar to the DDN, also at the DDE larger battery capacities (> 160 kWh) do not appear to have a positive influence on terminal performance. Current AGV idle times at the DDE in between two jobs create enough slack for AGVs to charge until a sufficient battery level. This idle time can be retrieved from Figure G.4 in Appendix G. Here, the average WT in *AvailableAGVs* resembles the idle time in between two jobs: this idle time is equal to 16.55 minutes. However, when having larger batteries, the frequency with which AGVs go charging is considerably lower, as can be deducted from the empty AGV trip fraction. For 120 kWh batteries, this fraction is 52.0% while 300 kWh batteries set this percentage at 46.2%, almost 6% lower. In contrast to the DDN, now a convex curve is observed which flattens from 120 kWh after which it becomes horizontal from 160 kWh. Apparently, there are constraints on the size of the battery, for which a desirable size is 160 kWh, almost similar to the industry's standard (VDL AGV has 180 kWh batteries, Kalmar's AGV 174 kWh batteries). The simulation outcomes thus do match with decisions made by AGV key players.

Looking at the percentage of QCs waiting for AGVs, an unusual relation is found as 60 kWh batteries drop this percentage to 8%. However, when looking at the average waiting time of QCs for available AGVs, it is seen that this waiting time equals 1121 seconds, while 160 kWh batteries cause QCs to wait for available AGVs on average 222 seconds. As a consequence, delays in turnaround times turn out to be much higher with smaller

Table I.2: DDE simulation model validation

	Simulation outcome	Actual value	Difference	Matching factor simulation - reality
Turnaround time MAIN [hours]	28.2	29,2	1	96.6%
Turnaround time BARGE [hours]	6.2	4.5	1.7	62.2%
Turnaround time FEEDER [hours]	7.9	7.6	0.3	96.1%
Containers handled per day [containers/day]	5860	5500-6000	-	within range

Table I.3: Base case for the DDE with the variables to be varied and the variation range

	Base case DDE	Range DDE
Number of AGVs [#]	200	[100, 150, 200, 250, 300, 400]
Battery capacity [kWh]	160	[60, 120, 160, 300]
Charging power [kW]	300	[100, 150, 200, 300, 600]
Number of charging spots	20	[5, 10, 15, 20, 30, 40]

batteries. This is confirmed by the empty trip fraction, which equals 61.8% for 60 kWh batteries and 48% for 160 kWh batteries: a significant increase in (necessary) empty trips to charging spots occurs which causes extra delay in the handling of containers. It must be noted that this study sketches an optimistic scenario of the relation between empty AGV trip fraction and terminal performance deterioration. As no physical interaction between AGVs during driving has been modeled, it is expected that more frequent trips to charging spots at the ASCs will lead to more congestion on the AGV grid thereby potentially delaying ship turnaround times even more. Including this physical interaction in the developed simulation model is therefore highly recommended in future research.

Charging power

For the DDE, a similar relation as for the DDN between charging power and terminal performance can be observed. A steep decrease in ship turnaround times is made when increasing the charging power from 100 kW to 150 kW after which the curve becomes flatter, although still decreasing with increasing charging output power. Now the reader is attended to pay close attention to the following: likewise the DDN and Table 6.4, Table I.4 for the DDE is created in which the average AGV charging times and quantities are shown per charging output power. What immediately can be noticed, is the difference in charging quantities per charge with 100 kW and 150 kW. Similar to the DDN, 28.5 kWh turns out to be insufficient for a single charge (as this is lower than 35 kWh); 43.3 kWh, on the other side, resulted to be more sufficient (although still insufficient given the large difference in TATs and QCs waiting for AGVs) looking at the flattening that occurs. A general conclusion can thus be drawn regarding the required charging quantity per charge, which is deducted from both the variation in battery capacities and charging powers for both the DDN and DDE: charging 35 kWh per charge results to be a bare minimum for deep sea container terminals in order to reduce terminal performance deterioration. This conclusion is confirmed by current ECT AGV consumption data from which the average energy consumption of AGVs currently driving on the Delta Terminal is obtained: 140 kWh is needed per AGV per day. From the simulation, it is observed that AGVs go charging once every 5 hours or roughly 5 times a day. Given the 35 kWh minimum charging quantity, the total charged energy per day equals 175 kWh, which approaches the required energy needed of 140 kWh. This finding is also very valuable for literature on AGV opportunity charging as distributing the total charging quantity required over multiple charging moments instead of only one does not cause severe terminal performance deterioration.

Table I.4: Average charging times and quantities at different output powers for the DDE

	100 kW	150 kW	200 kW	300 kW	600 kW
Average opportunity charge time [minutes]	17.1	17.3	14.9	12.4	9.5
Charged electric energy per charge [kWh]	28.5	43.3	49.7	62	95.0

Number of chargers

As already mentioned, determining the number of chargers needed for a given AGV fleet size seems to be very valuable for industry key players. Section 6.3 discussed this amount for the smaller side of the Delta

Figure I.1: Turnaround times per ship type and percentage of QCs waiting against the number of battery-electric AGVs driving on the DDE; the orange line comprises the diesel base case

Terminal; this section presents the results found for the DDE, given an equal charging output power and battery capacity of 300 kW and 160 kWh respectively. What can be observed from the results in Figure I.4 is the convex curve which, likewise the DDN, flattens at a ratio of 1 charger for 20 AGVs (10 chargers on a fleet size of 200 AGVs). This ratio is also observed for the DDN; apparently, a 1:20 ratio proves to be a bare minimum in order to reduce deterioration in terminal performance when making the transition to battery-electric AGVs. Although 3 chargers on 65 AGVs for the DDN results in 35 minutes delays in MAINS turnaround times, for the DDE these delays count up to 242 minutes, ie. 4 hours. This is highly undesirable as will be shown later when discussing the TCO analysis results, in which downtime costs for MAINS are included. For here, it is important to conclude that the amount of chargers needed for minimal performance deterioration non-linearly increases with increasing fleet sizes, as now 30 chargers seem to suffice on a fleet of 200 AGVs (ratio of 1:7), whereas the DDN required 6 chargers for 65 AGVs (ratio of 1:11). This non-linearity is explained by the larger travel distances AGVs must cover per single trip, which in case of relatively more frequent empty trips to a charging spot at stack side leads to disproportionately higher delays.

AGV opportunity charge threshold

During experimenting with the opportunity charge threshold for AGVs at the DDE, similar outcomes as for the DDN were observed. Therefore, it is decided not to discuss these outcomes again, other than to mention that there seems not to be a relation between terminal performance and the maximum battery level from which AGVs are allowed to opportunity charge their batteries.

I.2. Total costs of ownership analysis for the DDE

I.2.1. First stage experimenting

Likewise the DDN, the same variables have been varied for the DDE, only on a different range which can be retrieved from Table 6.1. The TCO outcomes are presented in Figure I.5. Again, similar shapes as the simulation experiment results, depicted in Figures I.1, I.2, I.3 and I.4, are observed which can be explained by the significant influence of downtime costs on the TCO. Whereas 25% of the DDN base case TCO was caused by downtime costs, for the DDE this percentage lies much higher: around 50%. It was thus expected that similar curves were to be obtained.

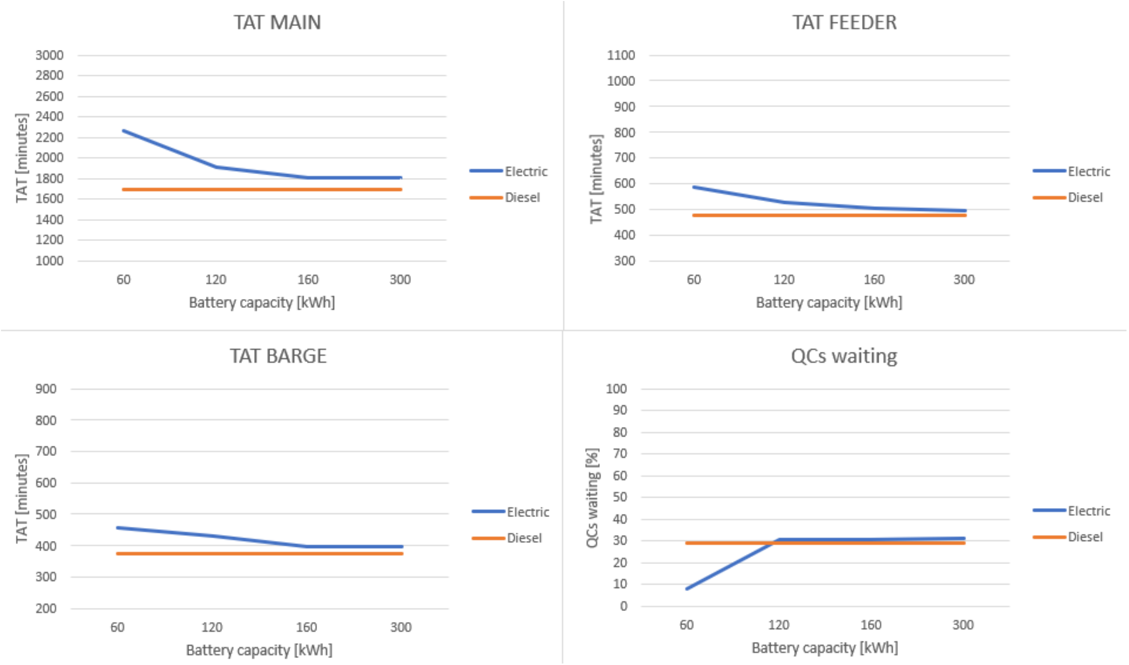


Figure I.2: Turnaround times per ship type and percentage of QCs waiting against different AGV battery capacities at the DDE; the orange line comprises the diesel base case

Number of AGVs

Figure I.1 shows that a fleet size from 300 battery-electric AGVs starts to outperform its diesel counterpart of 200 AGVs *given the base case configuration of 160 kWh batteries, 300 kW charging power and 20 quick chargers installed evenly along the stacks*. Similarly, the lowest extra total costs of ownership are achieved with this fleet size: purchasing more vehicles will be cost ineffective as the delays are already zero. However, it is doubted whether ECT is willing to increase its fleet size at the DDE with 50% as this will most likely increase congestion on the AGV grid and thus downtime. Since physical interactions between AGVs during driving have not been incorporated in the simulation model, the TCO may wrongfully conclude that adding 100 AGVs will result in zero downtime costs. Conclusions regarding the number of battery-electric AGVs to be deployed must thus be interpreted with care.

Battery capacity

Regarding the optimal battery capacity, 160 kWh turned out to be most cost effective which is in accordance with Figure I.2. Other than the DDN, at the DDE battery capacity appears to have an influence on the total costs of ownership since downtime costs decrease exponentially with higher battery capacities. Consequently, an optimum is found at 160 kWh *given the configuration of 200 AGVs, 300 kW charging power and 20 quick chargers*. Higher battery capacities press on the initial investment costs and battery replacement costs and are therefore unfavorable.

Charging power

From Figure I.5, it is perceived that higher charging powers result in a lower TCO; likewise, it was found that installing 600 kW at the DDE resulted in the lowest terminal performance deterioration. Since plug-in chargers currently on the market provide 600 kW power at most (see Table 3.4), decided is to set this variable's maximum value at 600 kW accordingly. What can thus be concluded is the higher charging power the more favorable TCO is obtained *given the configuration of 200 AGVs, 160 kWh batteries and 20 quick chargers along stack side*.

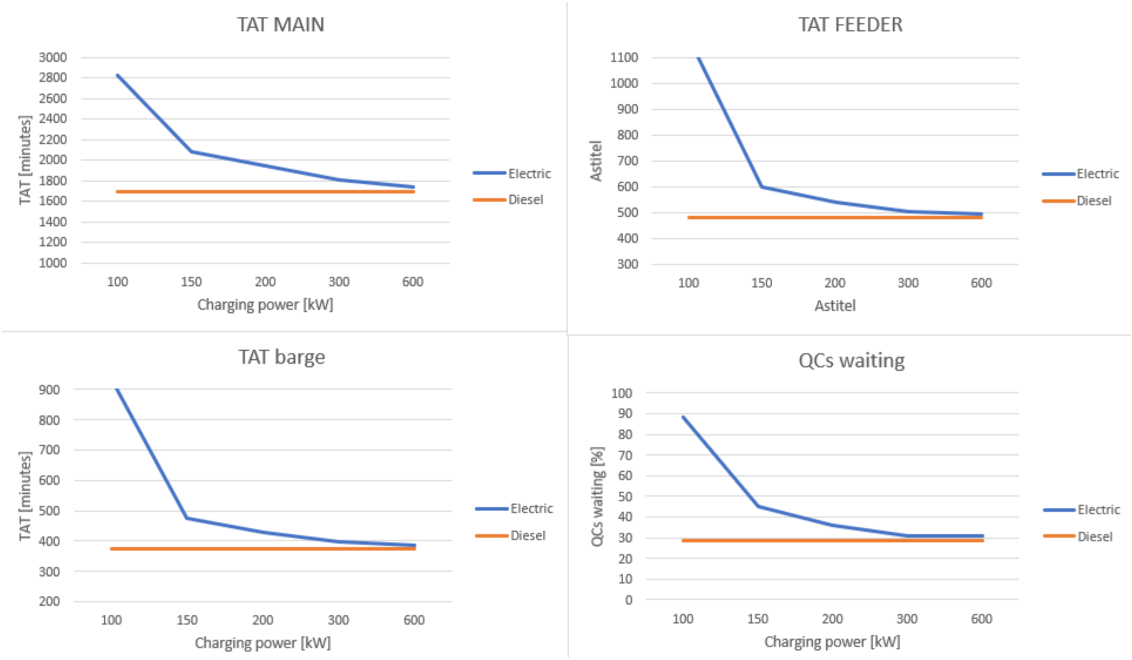


Figure I.3: Turnaround times per ship type and percentage of QCs waiting against different charging output powers at the DDE; the orange line comprises the diesel base case

Number of chargers

Finally, the number of chargers also appears to have a negative influence on TCO as adding more chargers leads to a smaller difference in TCO between diesel and battery-electric AGVs. This was also expected since Figure I.4 shows that from 30 chargers the improvement in operational performance becomes smaller.

I.2.2. Second stage experimenting

Regarding the DDE, it was found that 300 AGVs, 160 kWh batteries, 600 kW charging power and 30 chargers turned out to be most cost effective. Yet, again these ’optima’ were constrained by the defined base case for the DDE. Also, deploying 100 extra AGVs as are currently driving is highly undesirable from the perspective of ECT (there is simply not enough capacity for 300 AGVs) and for the TCO outcome (300 AGVs turned out to be not most cost effective). Therefore, it was decided to perform two TCO analyses: one with the same amount of AGVs as are currently operational and one where the amount of AGVs is increased with the same percentage as for the DDN (from 65 to 75 AGVs equals an increase of 23%). Furthermore, both analyses use 160 kWh batteries, 600 kW power and 30 chargers. The results are also shown in Table 7.7; it is observed that keeping the same amount of AGVs outperforms adding more AGVs as the increasing maintenance costs and initial purchase costs exceed the decrease in downtime costs of 27,000,000 euros. Though, diesel AGVs remain favorable over battery-electric AGVs as their TCO is more than 30,000,000 euros lower.

Finally, it is checked whether adding more chargers leads to a more beneficial TCO for the DDE as adding more AGVs proved not to be more cost effective. Instead of deploying 30 chargers, a set up with 200 AGVs and 40 chargers at 600 kW was analyzed. The results are also presented in Table 7.7. It is seen that this alternative leads to an even more favorable TCO, yet, the total costs of ownership remain higher than for diesel AGVs. The reader is attended that no generalizations can be drawn regarding adding more AGVs or installing quick chargers since in this study it is assumed that twice as much quick chargers and twice as much charging power lead to twice as much infrastructure costs. In reality, there is no such linear relation and this is thus a limitation of the performed TCO analysis. What can be concluded is that adding more quick chargers at the expense of purchasing more AGVs potentially could lead to lower lifetime costs due to the decrease in downtime costs since *relatively* more AGVs must be bought to achieve the same terminal performance when compared to the amount of quick chargers to be initially purchased.

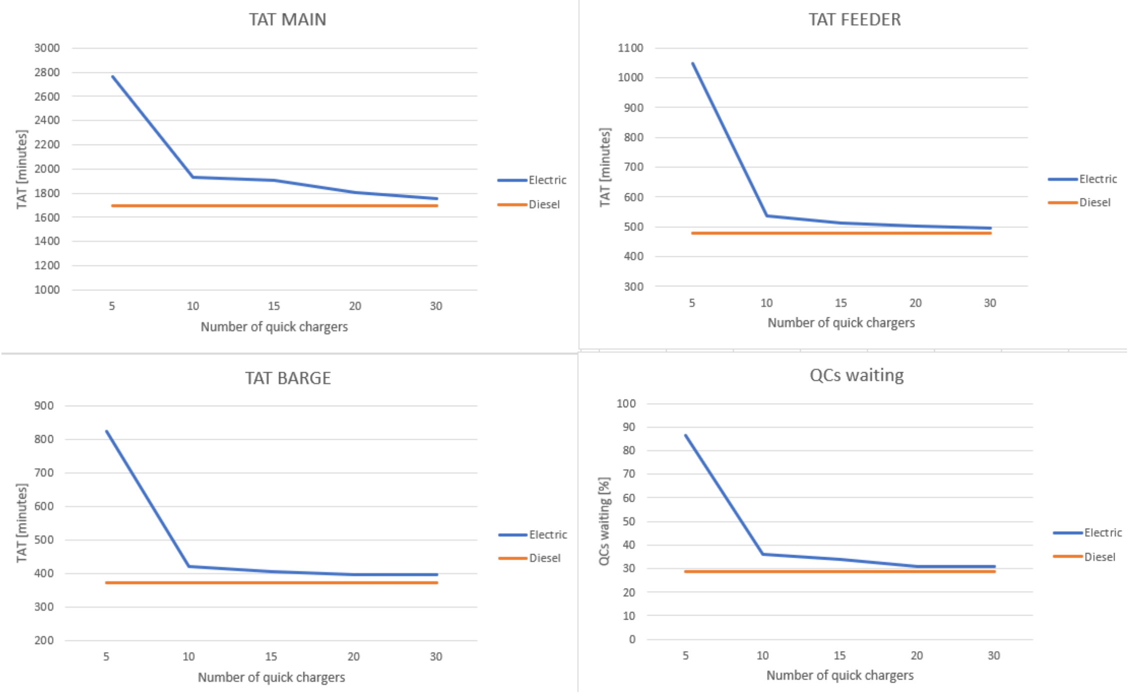


Figure I.4: Turnaround times per ship type and percentage of QCs waiting against various amounts of chargers installed along stack side at the DDE; the orange line comprises the diesel base case

I.2.3. Scenario analysis

By performing a similar scenario analysis on the DDE as for the DDN (see Figure 7.6), the results as depicted in Figures I.6 and I.7 are obtained for the most promising configuration (i.e. 200 AGVs, 160 kWh batteries, 600 kW charging power and 40 charging spots). It can be seen that with a slight increase in diesel price, a battery-electric AGV fleet proves to be more cost effective than their diesel counterpart. This is heavily caused by the substantial share of fueling costs in the total costs of ownership of diesel AGVs; a slight increase in diesel prices leads to significantly worse outcomes for diesel AGVs when compared to battery-electric AGVs. For the most pessimistic diesel price scenario and most optimistic electricity price scenario, this cost difference with diesel AGVs even counts up to more than 55 million euros, which implies that battery-electric AGVs have an even stronger financial potential at larger container terminals due to the substantial reduction in fueling costs.

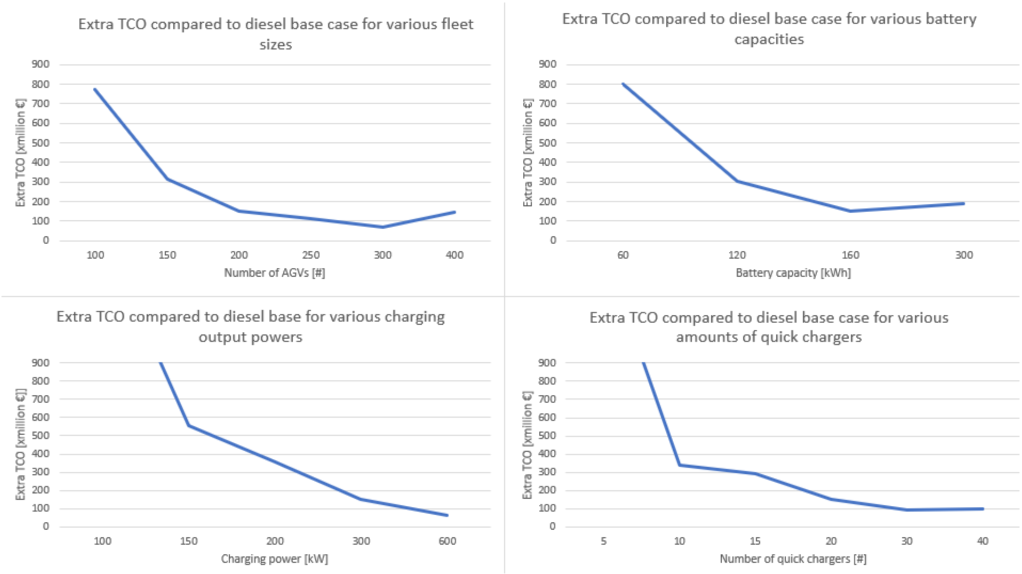


Figure I.5: Extra total costs of ownership of battery-electric AGV fleet variants when compared to the diesel DDE base case with 200 AGVs

Table I.5: Total costs of ownership of the most promising alternatives. For the DDE: 200 and 245 AGVs respectively, 160 kWh batteries, 600 kW charging power and 30 chargers for the first two alternatives. For the latter, 40 plug-in chargers are installed along the ASCs.

	DDE same amount of AGVs	**DDE +23% AGVs**	**DDE 40 chargers**
Capital expenditures			
Pilot costs	-	-	-
AGV purchase costs (including battery)	119,200,000	146,200,000	119,200,000
Charging infrastructure costs	23,600,000	23,600,000	31,433,333
Implementation costs	190,000	190,000	190,000
Total	**142,890,000**	**169,710,000**	**150,723,333**
Operational expenditures			
Fueling costs	21,063,161	21,222,023	20,818,241
AGV maintenance costs	55,200,000	67,620,000	55,200,000
Charger maintenance costs	2,700,000	2,700,000	3,600,000
Downtime costs	27,132,000	-	11,424,000
Disposal costs	3,200,000	3,920,000	3,200,000
Total	**67,195,161**	**45,328,623**	**50,027,241**
Incomes			
EIA subsidy	19,278,000	22,898,700	20,335,500
WBSO subsidy	12,000	12,000	12,000
Salvage incomes AGV	1,000,000	1,225,000	1,000,000
Salvage incomes battery	760,000	931,000	760,000
Total	**21,050,000**	**25,066,700**	**22,107,500**
Total costs of ownership	**231,135,161**	**240,105,323**	**222,858,074**
Cost difference with diesel AGVs	**31,998,648**	**40,968,810**	**23,721,561**

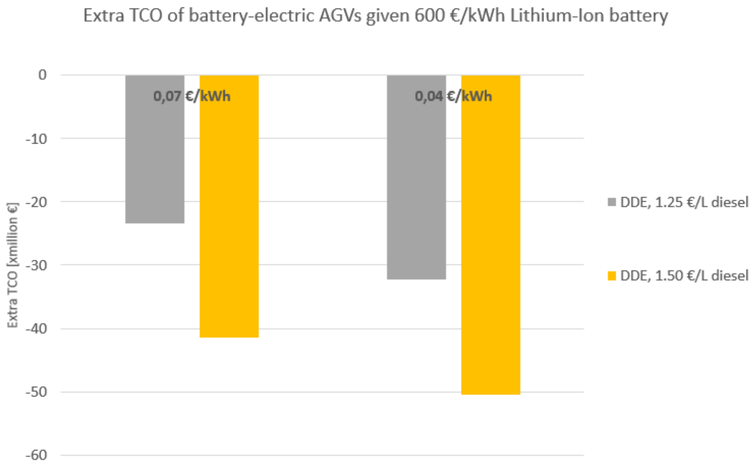


Figure I.6: Extra total costs of ownership of a battery-electric AGV fleet over a 15 years time horizon with a fixed 600 €/kWh Li-Ion battery price for the DDE

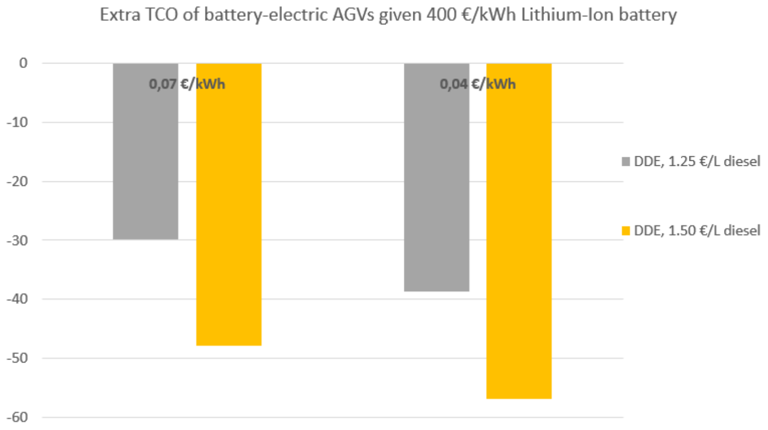


Figure I.7: Extra total costs of ownership of a battery-electric AGV fleet over a 15 years time horizon with a cheaper 400 €/kWh Li-Ion battery price for the DDE

J

Interviews and experts overview

Tables J.1 and J.2 provide an overview of the several interviews that have been held during this Thesis research and the experts from whom data have been obtained regarding:

- technical characteristics of diesel and battery-electric AGVs and Lithium-Ion batteries which have been used as input into the simulation and TCO models
- technical and operational characteristics of the Delta Terminal which have been used as input into the analysis, design and evaluation phases of this study
- operational Key Performance Indicators of both the DDN and DDE which have been used to validate the developed simulation model
- requirements and constraints for the design of the AGV charging process which have been used in the design phase of this study
- the values/estimates of the cost elements included in the total costs of ownership analysis which have been used in this study's testing/evaluation phase

Table J.1: Experts from whom necessary information is retrieved to perform this Thesis research

Name	**Function and organization**	**Main information provided**
Arie Vroegindeweij	Maintenance Engineer AGVs at ECT	1. Technical characteristics diesel and battery-electric AGVs 2. Energy calculations current diesel fleet 3. Maintenance costs calculations diesel and battery-electric AGV fleet
Alex Stevenson	Consultant Improvement and Development at ECT	1. Actual KPI values of the DDN and DDE side of the Delta Terminal 2. Operational characteristics of the Delta Terminal
Ivo van Hassel	Business Consultant Infrastructure and Equipment at ECT	Infrastructure cost estimation of the base case design configuration with 300 kW charging power and 6 chargers installed along ASCs
Paul Middelburg	Senior Consultant Infrastructure and Equipment at ECT	1. AGV and implementation related costs 2. Technical characteristics Delta Terminal 3. AGV related technical characteristics

Table J.2: Overview of the interviews held during this Thesis research

	Date	**Interviewee(s)**	**Subject**
Interview A	July 10, 2018	**Paul Middelburg** Senior Consultant Infrastructure and Equipment at ECT	Objectives and constraints for the AGV charging process design
Interview outcome	1. Technical constraints for the AGV charging process design 2. Main objectives of I&E and FD departments		
Interview B	July 10, 2018	**Alex Stevenson** Consultant Improvement and Development at ECT	Objectives and constraints for the AGV charging process design
Interview outcome	1. Operational constraints for the AGV charging process design 2. Main objectives of LD department		
Interview C	July 11, 2018	**Arie Vroegindeweij** Maintenance Engineer AGVs at ECT	Objectives regarding implementation battery-electric AGVs
Interview outcome	1. Main objectives of TOD department 2. Technical characteristics diesel and battery-electric AGVs		
Interview D	September 4, 2018	**Bob Bouhuijs** Director Automotive at Heliox	Technical and operational characteristics AGV batteries and charging infrastructure
Interview outcome	New insights into charging infrastructure for battery-electric AGVs		
Interview E	September 6, 2018	**Karel Smits** Manager Automated Vehicles at VDL **Jeroen van Herk** Product Manager Automated Vehicles at VDL	Technical and operational characteristics battery-electric AGV of VDL
Interview outcome	Practical insights into battery-electric AGVs' performance at container terminals		

K

Scientific paper

Evaluating the operational and financial feasibility of battery-electric AGVs at brownfield container terminals

I. Bouhannouche
MSc student Transport, Infrastructure and Logistics
Delft University of Technology
Delft, the Netherlands

J. M. Vleugel
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Delft, the Netherlands

Y. Pang
Faculty of Mechanical, Maritime and Materials Engineering
Delft University of Technology
Delft, the Netherlands

R. R. Negenborn
Faculty of Mechanical, Maritime and Materials Engineering
Delft University of Technology
Delft, the Netherlands

***Abstract*— Diesel-powered Automated Guided Vehicles (AGV) are currently deployed for container transport at terminal's water side. Looking at the trends in formal legislation and market developments towards sustainability, these diesel AGVs are most likely to become outdated. Although battery-electric AGVs are an emerging, zero-emission alternative, there are serious technical, operational and financial questions regarding their implementation at brownfield terminals operating 24/7. Taking the northern side of the ECT Delta Terminal in the port of Rotterdam as a case, the operational and financial feasibility of replacing diesel AGVs by a battery-electric AGV fleet have been evaluated by means of simulation and a total costs of ownership analysis. The results indicate that battery-electric AGVs opportunity plug-in charged at the automated stacking cranes' transfer points prove to be an operationally and financially feasible alternative to diesel AGVs: operationally under the condition that a sufficient amount of AGVs, charging power and plug-in chargers are installed and financially under the condition that the increasing trend in diesel price and decreasing trend in electricity price will continue in the near future. As environmental legislation for heavy-duty vehicles becomes more stringent while there is a decreasing trend in electricity prices, battery-electric AGVs are most likely to become profitable for deployment at brownfield container terminals. Therefore, this study's findings could pave the way for terminal operators to replace their environmentally unfriendly diesel AGVs by zero-emission vehicles, potentially becoming the key force increasing the global penetration rate of electric vehicles in heavy-duty industry.**

Keywords —Battery-electric AGVs, brownfield container terminals, simulation, total costs of ownership, ECT Delta Terminal

I. INTRODUCTION

As seaports are becoming more automated due to growing international container trade, transport of containers between seaside quay cranes (QC) and landside automated stacking cranes (ASC) is not being done anymore by human driven trucks. Instead, automated guided vehicles (AGV), self-driving vehicles that are capable of transporting 20 and 40 feet containers, are used for quay-stack transport [1]. Main advantages of deploying AGVs are labor cost savings, increased safety of employees, predictable operations and reduction of errors in the transport process [2][3]. Currently, most of the AGVs operating at container terminals are diesel-powered. However, as studied by Van Duin & Geerlings [4], diesel AGVs pollute by far the most carbon dioxide compared to other terminal equipment. Looking at the trends in formal legislation and market developments towards more sustainability due to increasing pressure on the government and industry, these diesel AGVs are most likely to become outdated and taken on first in terminal's environmental policy and its corresponding AGV replacement program. For example, on an international level the recent Paris Climate Agreement to reduce global warming to 2 degrees Celsius has urged the transportation sector to become more sustainable as this sector alone contributes to one-fifth of the total carbon dioxide emissions in the world [5][6]. Thereby, port authorities around the world are actively promoting sustainable terminal equipment [7][8].

In order to anticipate on stricter environmental regulations, container terminals are conducting research on battery-electric AGVs, an emerging, zero-emission alternative. Although battery-electric AGVs do not emit carbon dioxide and other greenhouse gases and thus appear to be a promising alternative for future legislation, the limited driving range and significantly longer replenishment times of the batteries compared to diesel tanks raises questions about the operational feasibility of deploying electric vehicles, especially in transport systems running 24 hours a day [9][10]. Next to operational concerns, battery-electric AGVs also require higher investment costs in both vehicles and charging infrastructure compared to diesel AGVs. Although electric propulsion is expected to result in lower operational expenditures due to the reduction in fueling and maintenance costs, terminal operators do not know if these potential fuel and maintenance savings over an electric AGV's lifetime outweigh the higher initial costs in batteries and infrastructure [11]. This lack of knowledge on the operational and financial feasibility of battery-electric AGVs compared to their current diesel AGV fleet has created a bottleneck for terminal operators to make a well-funded decision whether or not to purchase battery-electric AGVs for their next AGV replacement program.

From literature, a clear knowledge gap is observable regarding the operational and financial consequences of implementing a battery-electric AGV fleet at container terminals. It can be reasonably argued that terminal operators would only consider this zero-emission alternative if it is both operationally and financially viable. Therefore, the aim of this study is to evaluate the operational and financial feasibility of battery-electric AGVs at container terminals. Since diesel-powered AGVs are almost exclusively used at brownfield container terminals characterized by a fixed terminal layout, the focus of this study is obviously on brownfield rather than greenfield terminals. Taking the ECT Delta Terminal, the largest terminal operator of Europe, as a case, it was investigated whether it is operationally and financially feasible to replace their current environmentally unfriendly 65 diesel AGVs operating at the northern side of the terminal, the Delta Dedicated North (DDN), by a full electric AGV fleet powered by Lithium-Ion batteries; chosen is for Lithium-Ion rather than the more mature Lead-Acid technology due to its higher energy density. To do so, a functional design of the battery-electric AGV's charging process has been developed based on ECT's formulated requirements and constraints, which has been subsequently assessed on its operational and financial feasibility compared to the current diesel AGV fleet by means of simulation and a total costs of ownership (TCO) analysis.

More specifically, this research aims to answer the question *if it is operationally and financially feasible to replace diesel AGVs by battery-electric AGVs at brownfield container terminals* by providing answers to the following subquestions:

1. How are AGVs currently deployed during daily transport operations?
2. Where in the AGV operational process occur opportunities for battery charging?
3. Which design of the AGV charging process can be selected for evaluation on its operational and financial feasibility?
4. How does the design influence the operational performance compared to diesel AGVs?
5. To what extent is the design financially feasible compared to diesel AGVs?

The remainder of this paper is organized as follows. Section II provides the reader the state-of-the-art in charging battery-electric AGVs at container terminals and identifies the knowledge gaps relevant for this research. Section III presents the material and methods used to perform the simulation study and TCO analysis. Section IV goes in more detail regarding the structure, input and output of the developed simulation and TCO models, after which the results of both the simulation and TCO studies are presented in section V. Section VI ends with a conclusion and discussion of the performed research and provides suggestions for further research.

II. LITERATURE REVIEW ON BATTERY-ELECTRIC AGVS

Despite the potentially negative operational impact electric charging of AGVs at terminals may have, little research has been conducted on this topic [12]. Most studies on AGVs at container terminals use simulation to optimize routing and scheduling algorithms; they ignore the effect of electric charging of the batteries on the operational performance or consider it to be small [13][14][15][16][17]. Studies that have conducted research on electric charging of AGVs mainly focus on the total costs of ownership. Schmidt et al [18] investigated the effect of different charging strategies on total AGV costs. By analyzing data gathered from a comprehensive electric AGV project of the largest terminal operator of Germany using battery swapping as charging strategy and Lead-Acid batteries as energy storage unit, they found that shifting battery charging to electricity grid's off-peak hours results in the highest cost savings. On the basis of a simulation study, Schmidt et al [11] explored the minimum amount of exchange batteries required for a full electric AGV fleet to maintain the required operational performance, the so-called battery-to-vehicle ratio. By analyzing data gathered from another large electric mobility project and by performing a total costs of ownership analysis, they found that using a ratio of 16:10 - 16 batteries per 10 AGVs - could lead to 14% cost savings compared to the total expenditures for an AGV fleet. Finally, Ebben [19] shows by means of simulation that the number of batteries to be purchased for automated transportation networks does not heavily depend on the number of battery charging locations but merely on the battery type used. Ebben [19] also proposes a cost trade-off model to help the designer choose the type and optimal number of batteries for the transport fleet.

Although the studies discussed above seem promising in the field of AGV electrification, they all considered the batteries to be charged by means of a battery swapping station, in which empty batteries are replaced by spare ones. Since brownfield terminals often have limited space and flexibility left in their terminal design for these large charging facilities, these options are less viable from a brownfield operator perspective. Yet, terminals *do* offer, due to their closed nature, more alternatives for charging batteries, e.g. by means of quick charging at strategical locations [12][20]. McHaney [20] somehow included this potential in his research and presented three types of charging schemes to be simulated:

1. Automatic charging, in which AGVs with battery levels below a certain threshold value are assigned for charging
2. Opportunity charging, which uses idle and waiting times in an AGV's transport cycle to charge the battery
3. Combination of automatic and opportunity charging

McHaney [20] concluded that battery constraints cannot be ignored when modeling and simulating an AGV system. Furthermore, he has shown that opportunity charging contributes to a more efficient AGV fleet. However, this research mainly embedded *general* AGV systems in discrete event simulation rather than focusing on embedding automatic/opportunity charging strategies in container terminals. With terminals operating 24 hours a day and handling large ships with an amount up to 7500 TEU, the model of McHaney [20] simply cannot be used. Moreover, in his study McHaney [20] did not include the cost element while costs, next to operations, are the main selection criterion for terminal operators to purchase port equipment [21].

In their conference paper, Fatnassi & Chaouachi [22] propose a battery charging management strategy for AGVs in warehouses and factories by using linear programming heuristics. However, AGV deployment in factories, as opposed to container terminals, is characterized by long driving distances and short idle times, thereby limiting the potential of opportunity charging in these settings; for container terminals, driving distances are mostly short and waiting and idle times long. Also, Fatnassi & Chaouachi [22] considered battery charging at the edge of the operational area only. Though, as McHaney [20] mentioned, incorporating charging infrastructure in the transport cycle may result in higher operational effectiveness. Similar to Fatnassi & Chaouachi's [22] research, several studies have been conducted on the charging state estimation of AGV batteries [23][24]; all these studies, though, focus merely on robotic warehouse and manufacturing equipment rather than terminal equipment and characteristics. Bian et al [25] studied the dispatching of electric AGVs in fully Automated Container Terminals (ACT). By developing an event-driven assignment algorithm in which AGVs accomplishing jobs were considered as a linear min-sum assignment model, they concluded, similar to McHaney [20], that battery capacity constraints cannot be ignored when deploying electric AGVs. Though, Bian et al [25] go a step further and set up, by means of numerical experiments, an optimal assignment algorithm for dispatching electric AGVs. Yet, Bian et al [25] focused on ACTs with long AGV traveling distances; most container terminals, however, are characterized by short and frequent trips. They also excluded simulation from the research scope: although optimal assignment algorithms can still be determined with numerical evaluation, stochasticity cannot be captured with this method while container terminals are characterized by stochastic events (in terms of container arrival and handling times).

From this literature review, it can be concluded that there is a clear knowledge gap in literature regarding the operational and financial feasibility of a battery-electric AGV fleet at *brownfield* container terminals. For greenfield terminals with terminal layout freedom, the study of Schmidt et al [11] may suit well: battery-electric AGVs appear to be operationally and financially feasible if large swapping stations are used for battery charging. However, for brownfield terminals this study misses the fundamental characteristic that distinguishes brownfield from greenfield terminals: spatial and operational restrictions. Regarding the studies of McHaney [20] and Fatnassi and Chaouachi [22], the setting in which AGVs are deployed is a factory with short idle times and long driving distances. Container terminals, on the other side, provide short driving times between the quay cranes and the stack and relatively long waiting and idle times, e.g. due to berthing of ships. Outcomes of these studies may thereby not be generalizable to all types of closed transport systems. Finally, most studies on electric AGV charging consider Lead-Acid battery technology only for deployment at container terminals due to its maturity. Studies that *have* taken into account various battery types for electric AGVs, however, have not yet considered the newest technology with a high energy density: Lithium-Ion batteries. With the rise of Lithium-Ion batteries, battery constraints on AGV's driving range may potentially be ignored and is therefore worth investigating within this study.

III. MATERIAL AND METHODS

This study's key contribution to current literature is an operationally and financially feasible concrete design of the battery-electric AGV charging process for brownfield container terminals with space constraints. To achieve this, an adapted version of the design approach of Sage & Rouse [28] has been applied in this study by distinguishing three research phases:

1. *Research object analysis*, in which the current state in AGV operations is studied. By statistically analyzing AGV activity time stamps from a large data set with more than 10,000 data points, the most promising moments and locations for battery charging have been obtained, making use of AGV waiting and idle times.
2. *Selection of alternative design*, in which the most promising design of the AGV charging process, best fitting the activity patterns found in the previous phase, is selected on the basis of brownfield operator's formulated design requirements and constraints. The used methodologies within this phase are literature research, expert interviewing and functional decomposition by means of a morphological chart.
3. *Evaluation of selected design*, in which the selected alternative of the previous phase is evaluated on its operational and financial feasibility by means of simulation and a total costs of ownership analysis respectively.

A brownfield container terminal was selected as a case to enhance the validity of the results.

A. Case study description

To evaluate the operational and financial feasibility of replacing diesel AGVs by battery-electric AGVs, the northern side of the ECT Delta Terminal, the DDN, is chosen as a case study. At the DDN, 65 diesel-powered AGVs are currently operating which are daily responsible for the transshipment of 2500-3000 containers, yielding an annual capacity of 1 million TEU[1]. The waterside of the DDN, the area of interest for this study, has a surface area of 124,000 m^2 and a quay length of 1040 meters, allowing two deep sea vessels and one barge vessel to moor at the same time. An amount of 10 QCs discharge and load containers from/onto mooring vessels, taking care of the container handling operations at quay side. At landside, 34 ASCs are responsible for the organization of the container yard; each ASC has four AGV loading and unloading spots. In

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[1] Twenty foot Equivalent Unit

between the QCs and ASCs, the so-called AGV area, AGVs are responsible for container transport between landside and seaside. All QC, AGV and ASC activities are centrally controlled by a Terminal Operation System (TOS).

Within this study's context, all 65 diesel-powered AGVs are assumed to be replaced by a battery-electric AGV fleet powered by Lithium-Ion batteries. Main difference between a diesel and battery-electric AGV lies in both the source of energy and kinetic energy generation: while diesel AGVs obtain their kinetic energy from a diesel engine which uses diesel from a fuel tank, battery-electric AGVs are powered by electrical motors which receive their energy from traction batteries with a significantly lower energy density compared to diesel tanks [9][10]. Wischemann [26] showed that Lead-Acid battery-electric AGVs have a substantially higher well-to-wheel efficiency than their diesel counterpart, 56% versus 26%, while having similar performance characteristics in terms of failure rate and speed. As this study considers Lithium-Ion batteries, the expected well-to-wheel efficiency is even higher: 66% in the most conservative scenario [27]. Additional benefit of using Lithium-Ion batteries over Lead-Acid technology is the absence of toxic materials with regard to environmental friendliness and disposal costs [36].

B. *Application of the design approach*

1) *Research object analysis*

All actions an AGV takes during a discharge and loading trip have been statistically investigated. Within the 24/7 operational process, most of the time AGVs are either waiting at the ASC and QC transfer points for their container to be (un)loaded by the ASCs and QCs, waiting at the ASC transfer points until they get 'permission' from the TOS to start driving to the QC lane or idling at the ASC transfer points in between two transport jobs. Looking at Figure 1, it is seen that most opportunity for battery charging occurs at the ASC transfer points and to a lesser extent in the QC lane, given a total time of 45 minutes in between the start of two subsequent jobs for a single AGV. Figure 2 visualizes these most promising locations at the DDN. This information has been consequently used as input into the design phase.

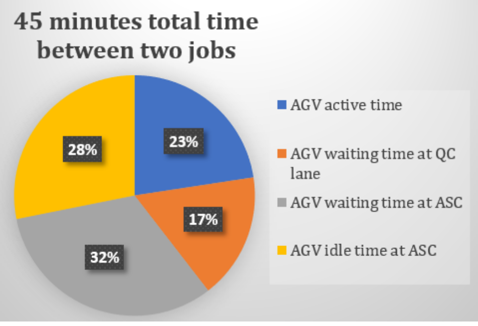

Figure 1: AGV active, waiting and idle time distribution

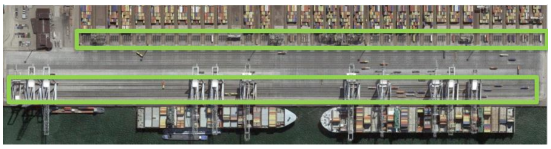

Figure 2: Most promising charging locations highlighted in green

2) *Selection of alternative design*

On the basis of design requirements and constraints, an alternative design of the AGV charging process has been selected for further evaluation. While the main design requirements follow from this study's problem definition, equal operational and financial performance compared to a diesel AGV fleet, design constraints were retrieved by interviewing experts of the case study's problem owner, ECT. By means of a morphological chart, the charging process has been functionally decomposed into its core system functions, *when*, *where* and *how to charge*, after which alternatives for each system function have been compared on both their constraints and requirements satisfaction. From this two-stage filtering process, *opportunity plug-in charging at the ASC transfer points* turned out to be the most promising functional design of the AGV charging process. Opportunity charging is chosen on the basis of two criteria mentioned by McHaney [20]: predictability of AGV routes and share of waiting and idle times. Whenever AGV routes are predictable and the share of waiting and idle time is substantial, which is indeed the case at centrally controlled container terminals, opportunity charging suits well as charging strategy. Regarding the choice for plug-in charging, Table 1 is of good use. Looking at this table, it is observed that plug-in charging outperforms the other considered charging techniques as it is cheaper while performing operationally equally well as pantograph charging. Finally, the ASC transfer points have been chosen as charging spot as most waiting and idle times occur at this location while the distance to AGVs is minimized.

		Plug-in	**Panto-graph**	**Rail**
Opera-tional criteria	Maximum charging power [kW]	600	600	120
	Charging efficiency [%]	97	97	97
Cost criteria	Infrastruc-ture costs [€]	200,000	300,000	1,000,000
	Maintenance sensitivity	+/-	+/-	-

Table 1: Operational and cost evaluation of the charging techniques

3) *Evaluation of selected design*

For the operational evaluation of the selected AGV charging process design, discrete event simulation has been chosen as methodology due to its ability to resemble the discrete nature of container transshipment at terminal's waterside, in which AGVs, QCs and ASCs subsequently wait on each other during container (un)loading. As analytically modeling AGV activities at the operational level is very complex, simulation also offers the user the ability to quickly run various scenarios for which analytical derivations would take significantly more time. The purpose of the developed simulation model is to compare the operational performance of a diesel AGV fleet and battery-electric fleet opportunity plug-in charged at the ASC transfer points. In order to do so, operational performance has been operationalized into *average turnaround time of deep sea vessels*, *QC productivity* and *QC utilization rate* as these factors are considered key in determining the terminal performance [29]. The simulation model has been built for diesel AGVs by default after which the model has been extended and adjusted to electric AGVs in order to compare both simulation outcomes. Regarding the financial evaluation of a battery-electric AGV fleet, a TCO analysis has been applied which Ellram [30] defined as "all costs associated with the acquisition, use and maintenance of an item instead of just the purchase price". Although battery-electric AGVs are more expensive in purchase price, their maintenance and fueling costs are expected to compensate this initial investment, for which a TCO analysis suits well as it considers the entire AGV lifetime [11]. The cost elements framework of Schmidt et al [11], depicted in Figure 3, has been applied in this study, however, downtime costs are added to the battery-electric AGV fleet as charging batteries is expected to decrease AGV's transport performance. Downtime costs were obtained by monetizing the delay in deep sea vessel turnaround times as terminal operators consider turnaround time delays as theoretical loss of their terminal capacity [33][34].

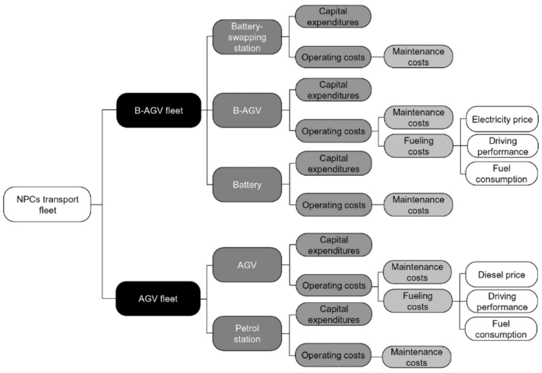

Figure 3: Cost elements framework of Schmidt et al [11]

IV. SIMULATION MODEL

A discrete event simulation model of the DDN AGV area has been developed in Borland Delphi with TOMAS extension. The DDN equipment configuration as presented in Figure 4 has been used as terminal layout for both the diesel and battery-electric AGV variants with corresponding x and y coordinates. Main difference, though, for the battery-electric variant is that the current two tanking spots at the edge of the AGV area are replaced by charging spots installed along the ASC transfer points, as highlighted at the top of Figure 2 and zoomed in on in Figure 5. This design implies that in potential 34x4=136 charging spots could be installed at the DDN, providing a significantly higher capacity and shorter AGV traveling distances than when installing chargers at the edge of AGV area.

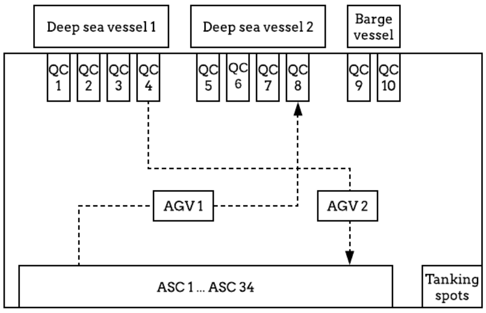

Figure 4: Terminal and equipment configuration of the DDN implemented in the simulation model

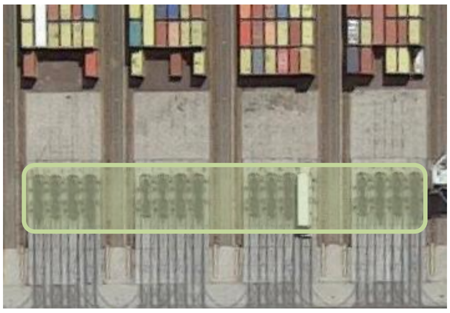

Figure 5: Potential charging spots at the ASC transfer points highlighted in green

A. Simulation model procedures

In the model, two separate processes are integrated: the operational process, i.e. AGV container transport which is considered the main terminal process, and the refueling process which is considered a subprocess. Whereas the operational process is fixed throughout the diesel and battery-electric variant, the refueling process varies.

1) Operational process

QCs, AGVs and ASCs form the core of the simulation model. Each container waiting on a mooring vessel or in the storage area either follows the handling sequence QC-AGV-ASC or ASC-AGV-QC, for which both the sequences are visualized in Figure 6. Solid arrows represent actions to be undertaken, dotted arrows represent interaction between model elements, which is necessary to let the other equipment 'know' what to do next.

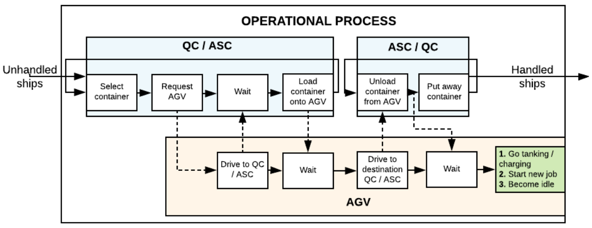

Figure 6: Structure of the operational process implemented in the simulation model

QC

Whenever a vessel moors along the quay wall, QCs start requesting an available AGV after selecting a container to be handled. After AGV arrival, QCs load containers according to a predefined handling time distribution onto an AGV. In case of vessel loading, containers are unloaded from waiting AGVs on the QC transfer points and subsequently loaded onto the ship according to the same handling time distribution; exact container locations on the ship are not modeled as this is out of this study's scope. In principle, there is an infinite amount of AGV spots per QC since AGVs are also queuing in the QC lane in reality (see Figure 2).

ASC

Similar to QC operations, ASCs handle containers from and onto AGVs, only in reverse order. During discharge of a vessel, containers are unloaded from arriving AGVs and subsequently put away in the stack according a predefined ASC handling time distribution. In case of vessel loading, ASCs select a container and start to request an idle AGV for container transport. Also here, the exact container locations in the stack has not been modeled; each ASC has four loading and unloading spots.

AGV

AGVs are responsible for quay-stack transport. When requested by a QC or ASC, an AGV starts to drive empty to the corresponding QC's or ASC's transfer point, after which it waits until it gets its container loaded on top. Then, the AGV drives loaded to its destination ASC or QC – it depends where it came from – and waits until its container has been unloaded. Physical interactions between AGVs during driving are not included. AGV's energy consumption varies for an empty and loaded ride: diesel AGV's energy consumption has been deducted from Van Duin & Geerlings [4], Lithium-Ion battery-electric AGV's energy consumption has been calculated using Wischemann [26] and Sun [27]. After a successful container delivery, the operational process is finished and the refueling process becomes active.

2) Refueling process

Regarding the refueling process, *tanking* and *charging* have been considered for the diesel and battery-electric AGV model respectively.

Tanking

When a diesel AGV has successfully delivered a container, it is checked whether its fuel load has dropped below a certain threshold value; ECT's diesel AGVs manage a 200 liters threshold level. If this is indeed the case, it is checked whether there are no QCs and ASCs requesting AGVs for container transport. If this is also true, AGVs are allowed to drive to the nearest free tanking spot located at the edge of the AGV area. Figure 7 graphically shows this implemented tanking logic.

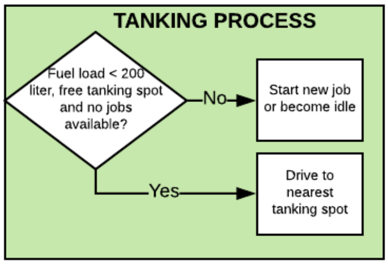

Figure 7: Implemented AGV tanking logic

Charging

To account for the selected charging design, opportunity charging has been implemented in the simulation model by means of a two-step decision structure. In case an electric AGV's battery level has dropped below 20% of its capacity, the AGV always goes charging to prevent deep battery discharges which could significantly shorten a battery's lifetime [31]. Also, if there are no transport jobs available while an AGV's battery level is still sufficiently high, AGVs are allowed to go charging at the nearest ASC charging spot. Figure 8 visualizes this decision logic in more detail. Key in the interaction between operational and charging process is the implemented hierarchy: whenever a QC or ASC requests an AGV, it is allowed to claim an AGV which is either charging, waiting for charging or driving to a charging spot, while guaranteeing a sufficient battery level. Using this structure thus leads to a higher chance of achieving the required terminal performance as the amount of AGVs available for transport jobs will be higher than when this extra 'AGV pool' would have been left out of QC/ASC selection.

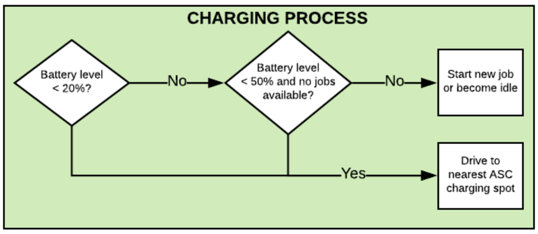

Figure 8: Implemented AGV charging logic

A final note is made on the tanking and charging time. While tanking takes on average 5-10 minutes, based on tanking data provided by ECT, and is not very sensitive to the actual quantity tanked, charging Lithium-Ion batteries *does* depend on the remaining battery level. Van Kooten Niekerk et al [31] found that charging a Lithium-Ion battery from 0 to 80% battery level takes approximately the same time as charging from 80 to 100% due to the battery's lower energy receptiveness after the 80% level. Therefore, within this study the battery replenishment time has been calculated using the following formula:

$$t_{charge}\ [h] = \frac{0\text{–}80\%\ of\ capacity\ [kWh]}{charging\ power\ [kW]*\eta} + \frac{80\text{–}100\%\ of\ capacity\ [kWh]}{\frac{1}{4}*charging\ power\ [kW]*\eta}$$

in which the charging time in hours t_{charge} depends on the remaining battery level relative to its capacity, the charging power and the charging efficiency η (see Table 1, 97%).

B. *Simulation model input and output*

The model input is shown in Table 2; a difference is made in layout values and operational parameters. To resemble the DDN as much as possible, all operational input parameters are fitted on actual ECT data. Main outputs of the model are operational performance indicators such as QC productivity, QC utilization rate and deep sea vessel turnaround times. For the remainder of this paper, the average turnaround time of deep sea vessels is discussed only as the other performance measurements showed to be strongly related to this criterion.

	Parameter	**Value**	**Unit**	**Data source**
Layout	Size of terminal	1040x120	m	Delta view
	# QCs per deep sea vessel	4	-	Delta view
	# QCs per barge vessel	2	-	Delta view
	Longitudinal separation QCs	50-75	m	QC data
	# ASCs	34	-	Delta view
	Longitudinal separation ASCs	25	m	Delta view
Operational	Average AGV speed	2.75	m/s	AGV data
	AGV fuel consumption	varies[2]	-	[4][26][27]
	QC handling time	N(μ, σ)[3]	s	QC data
	ASC handling time	N(μ, σ)[3]	s	ASC data
	Interarrival time deep sea vessels	Exp(λ)[3]	h	Sailing data
	Interarrival time barge vessels	Exp(λ)[3]	h	Sailing data
	Container discharge size deep sea vessels	N(μ, σ)[3]	cont	Sailing data
	Container load size deep sea vessels	N(μ, σ)[3]	cont	Sailing data
	Container discharge size barge vessels	N(μ, σ)[3]	cont	Sailing data
	Container load size barge vessels	N(μ, σ)[3]	cont	Sailing data

Table 2: Input parameters of the simulation model

C. *Verification and validation*

The simulation model has been verified and validated with measured data and expert knowledge from the actual system. The model proved to function according its specification by tracing all activities during a simulation run and did not show irregularities regarding model output. A sensitivity analysis performed on the AGV speed and fuel consumption, the most uncertain input of the model, showed that the model output is not sensitive to changes in AGV fuel consumption while it is sensitive to changes in AGV speed, though in the expected direction. A higher AGV speed leads to a substantial improvement of terminal performance as containers will be transported faster. Finally, by comparing simulation outcomes with actual ECT KPI values it was observed that the simulation model is closely according to reality as all KPI values had a matching factor of more than 80%, with QC productivity and QC utilization rate reaching a 91-96% matching factor.

D. *Experimental plan*

As this study's main objective is to gain insight into the operational and financial feasibility of battery-electric AGVs compared to the current situation with diesel AGVs, experiments are conducted with the battery-electric AGV model only; the diesel AGV model is left at its base case to represent the current actual state at the DDN and to serve as a reference for operational and financial feasibility. By means of a literature research, the *number of AGVs*, *battery capacity*, *charging power* and *number of chargers* were chosen as influencing variables for the determination of operational and

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[2] Different for the diesel and battery-electric AGV variants

[3] Distribution under confidentiality agreement

financial feasibility and have been consequently parametrized in the battery-electric AGV model [11][18][20]. By defining the base case as shown in Table 3, each variable has been varied on their defined ranges to assess the individual influence on the operational and financial performance of the DDN.

Each simulation has been run for 146 simulation days to reduce the influence of the warm-up period; experiments were replicated three times according to the confidence interval method [32]. Operational and layout inputs are as shown in Table 2.

	Base case	Range
Number of AGVs [#]	65	[35, 50, 65, 80, 95]
Battery capacity [kWh]	160	[60, 100, 160, 220]
Charging power [kW]	300	[100, 150,200, 300, 600]
Number of chargers [#]	6	[2, 3, 4, 6, 8, 12]

Table 3: Experiment base case and range values

V. MAIN RESULTS

In this section, the main results of the simulation and TCO experiments are presented for a future battery-electric AGV fleet operating at the DDN side of the ECT Delta Terminal.

A. Evaluating the operational feasibility

According to the experimental plan, Figures 9, 10, 11 and 12 are obtained which graphically show the relation between each experimental variable and the terminal performance in terms of average deep sea vessel turnaround times in blue. The red line serves as the diesel reference and resembles the current operational performance at the DDN.

1) Current state

From Figure 9, it can be seen that with the current amount of 65 AGVs the turnaround time of deep sea vessels is slightly higher when deploying battery-electric AGVs. When increasing this number to circa 75 AGVs, the turnaround times of both fleets become equal. Further increasing this number does not improve terminal performance significantly as the QC capacity starts to function as the constraining factor (limited moves/hour due to manual operation), given the crane configuration at the DDN with limited twin carry capability.

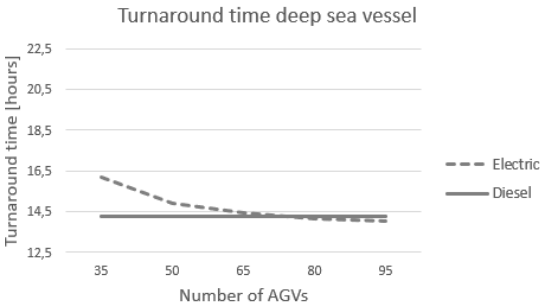

Figure 9: Influence of varying amount of battery-electric AGVs on operational performance

Looking at Figure 10, battery capacity surprisingly does not seem to correlate with terminal performance over the entire experimental range. Apparently, battery-electric AGVs compensate lower battery capacities with more frequent opportunity charging, as was observed from the empty AGV trip fraction. Reducing the capacity from 220 kWh to 60 kWh led to an increase in the empty AGV trip fraction, i.e. the fraction of empty AGV trips over the total amount of trips, from 46% to 50% respectively. More importantly, frequent charging trips did not appear to result in terminal performance deterioration, which can be explained by the high share of idle and waiting times in an AGV's transport cycle. Seemingly, the idle time in between two jobs, 15 minutes, is enough to charge the AGV to a sufficient battery level, as is confirmed by the average charging time of 11 minutes.

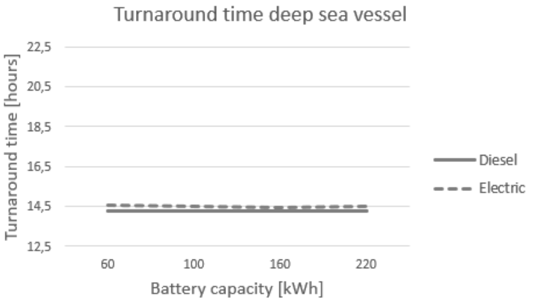

Figure 10: Influence of various battery capacities on operational performance

Figure 11 shows the relation between the speed of charging, operationalized in charging power in kilowatt, and operational performance. As can be seen, a significant gain in performance is made when increasing the charging power from 100 to 150 kW, after which the average turnaround time slowly further decreases until the diesel reference line at 300 kW. Likewise the battery capacity curve, this convex relation can be explained by the AGV idle times in between two job, though in more detail. By tracing the charging times at different charging powers, it was perceived that with 100 kW almost the whole idle time was occupied for charging, while with higher charging powers this occupation rate was considerably lower. Apparently, to meet the required daily AGV energy demand at the DDN, 140 kWh, and taking into account the observation that AGVs went charging once every 5 hours during a simulation run, 100 kW is not sufficient as an AGV could charge within the given idle time frame in the most optimistic scenario 125 kWh (100 kW x 0.25 h x 5), which is insufficient for the required daily demand.

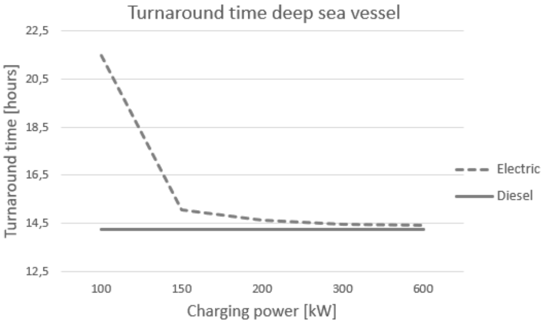

Figure 11: Influence of various charging power on operational performance

Finally, the amount of charging spots versus deep sea vessel turnaround times is graphically depicted in Figure 12. It is assumed that the chargers are equally distributed along the available ASC transfer points. A convex relation is observed which flattens at 3 charging spots. Also here, the AGV idle times prove to be an explanatory factor. Though, merely relevant for this study is the amount of chargers needed to reach operational feasibility: 6 chargers seem to suffice. From this point, marginal improvement in terminal performance is made.

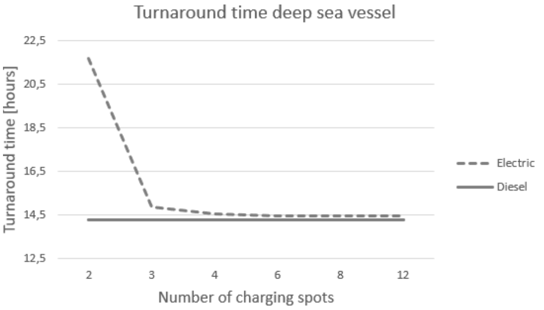

Figure 12: Influence of varying amount of chargers on operational performance

2) Future state

Next to the current state, a battery-electric AGV fleet's operational performance for the future state has been assessed. For this means, the variable values which are most promising to ensure operational feasibility have been combined in a joint configuration. From the previous results, it is seen that 75 AGVs, 300 kW charging power and 6 chargers roughly lead to operational feasibility; battery capacity is left at its base case value as it did not appear to correlate with operational performance (see Figure 10). By sequentially increasing the QC handling capacity and ship call sizes with 40%, the results as shown in Table 4 are obtained. The results indicate that battery-electric AGVs prove to be an operationally robust alternative which are resilient to future growth in terminal throughput; both fleets perform operationally equal under both growth scenarios.

		Current state	**+40% QC handling capacity**	**+40% ship call sizes**
Diesel	Deep sea vessel turnaround time [hours]	14.3	10.2	18.6
	QC productivity [mvs/hour]	23.0	36.9	21.4
	QC utilization [%]	76.4	74.0	71.1
Battery-electric	Deep sea vessel turnaround time [hours]	14.3	10.1	18.5
	QC productivity [mvs/hour]	23.0	37.0	21.5
	QC utilization [%]	76.5	74.1	71.4

Table 4: Simulation results of the future growth scenarios

B. Evaluating the financial feasibility

All parameters and values necessary to perform a TCO analysis for both the diesel and battery-electric AGV fleet are presented in Table 5. A time horizon of 15 years is applied as this is the common lifetime of an AGV [11][18]. Similar to the assessment of the operational feasibility, the experimental plan of Table 3 has been applied for the financial analysis.

	Value	**Data source**
Capital expenditure elements		
AGV costs [€/AGV]	500,000	Project data
Battery costs per kWh Li-Ion [€/kWh]	600	Project data
Plug-in charger costs [€/charger]	200,000	Project data
Charging infrastructure costs [€]	Under confidentiality agreement	Project data
Implementation costs [€]	Under confidentiality agreement	Project data

Operational expenditure elements		
Price per kWh electricity [€/kWh]	0.07	Project data, [35]
Price per liter diesel [€/L]	1.00	Project data
Surplus maintenance costs diesel AGV over 15 years [€/AGV]	Under confidentiality agreement	Project data
Annual charger maintenance costs [% of purchase price]	3	Project data
Annual petrol station maintenance costs [€/year]	Under confidentiality agreement	Project data
Delay costs deep sea vessel turnaround time per hour [€/hour]	Under confidentiality agreement	Project data
Disposal costs Li-Ion battery [€/battery]	16,000	[36]
Income elements		
Subsidy zero-emission vehicles [% of investment costs]	13.5	[37]
Subsidy retraining employees [% of retraining costs]	30	[38]
Salvage value AGV [€/AGV]	Under confidentiality agreement	Project data
Salvage value Li-Ion battery [€/battery]	3,800	[39]

Table 5: Input parameters used to calculate TCO of diesel and battery-electric AGV fleets

Looking at Figure 13, it is observed that an amount of 75 AGVs results in the lowest TCO for a battery-electric AGV fleet. From this amount, no gain is made in improving the operational performance as 75 battery-electric AGVs already lead to equal operational performance regarding the criteria relevant for this study, i.e. deep sea vessel turnaround times, QC productivity and QC utilization rate. Therefore, adding extra AGVs from this point unnecessarily results in higher costs.

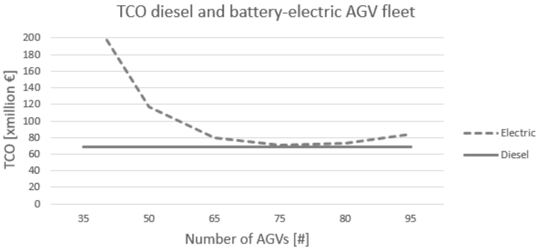

Figure 13: Influence of varying amount of AGVs on TCO of battery-electric fleet

Figure 14 graphically shows the relation between varying battery capacity and TCO; likewise the operational analysis, battery capacity does not tend to correlate with TCO due to the fixed downtime costs that occur. However, a marginal optimum is found at 160 kWh.

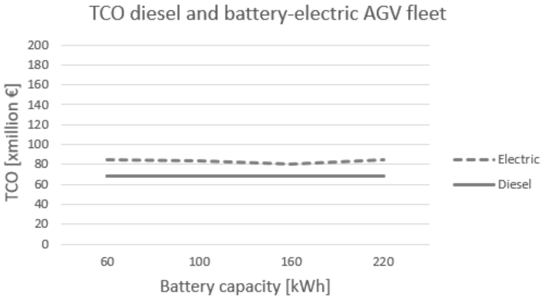

Figure 14: Influence of various battery capacities on TCO of battery-electric fleet

From Figure 15, it is perceived that a charging power of 300-600 kW results in the lowest TCO for a battery-electric AGV fleet. This is mainly the result of the lower downtime costs that occur with this charging speed, as was observed with the operational analysis.

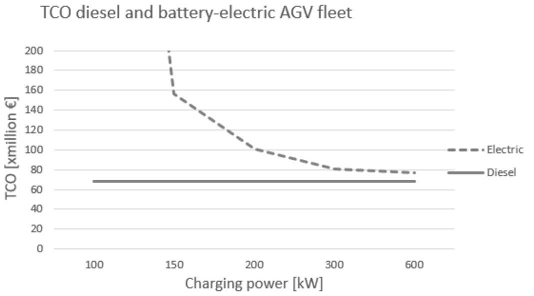

Figure 15: Influence of various charging power on TCO of battery-electric fleet

Finally, Figure 16 visualizes the relation between the amount of charging spots and the TCO. The results indicate that 6 chargers result in the lowest cost difference compared to the diesel base case, which is in accordance with the relation obtained from the operational analysis. Purchasing and installing more than 6 chargers unnecessarily adds to the total costs of ownership.

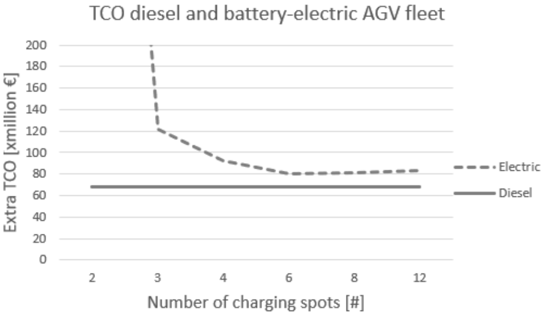

Figure 16: Influence of varying amount of chargers on TCO of battery-electric fleet

From the experiment results, it is observed that 75 AGVs, 160 kWh battery capacity, 300 kW charging power and 6 charging spots lead to the lowest cost difference with diesel AGVs. This financially promising configuration is similar to the configuration that has been evaluated on its operational feasibility in the previous section: a potential explanation lies in the high share of operational downtime costs in the total costs of ownership of a battery-electric AGV fleet. Consequently, this operationally feasible design configuration has been selected for further evaluation on its financial feasibility by means of a sensitivity analysis.

C. Evaluating the operational and financial feasibility

For the sensitivity analysis, the diesel, electricity and battery prices have been varied; consulting project data and [35], it was observed that the diesel price is most likely to increase while the electricity and battery prices are most likely to decrease within the near future. The results of this sensitivity analysis are presented in Table 6; it is perceived that under all defined scenarios a battery-electric AGV fleet becomes financially feasible and viable over diesel AGVs. More specifically, it is observed that especially future increases in diesel price could result in a positive TCO for battery-electric AGVs compared to diesel AGVs. This is explained by the fact that, unlike AGV maintenance costs, improvement in operational expenditures is mostly made by the reduction in fueling costs, which cause around 25% of the TCO of diesel AGVs while only 6% of the battery-electric AGVs' lifetime costs. With this in mind, it can easily be reasoned that especially the diesel price is a decisive factor in determining the financial feasibility of battery-electric AGVs compared to diesel AGVs rather than the electricity price: slight increases in diesel prices substantially influence the TCO of diesel AGVs and thus the cost difference with electric vehicles. The Li-Ion battery price appears not be a crucial factor for the financial feasibility as even with current Li-Ion price levels battery-electric AGVs prove to be financially viable over diesel AGVs. Hence, overall it can be concluded that, assuming that the current trend in diesel and electricity prices will continue in the (near) future, battery-electric AGVs prove to be a more cost-effective alternative than their diesel counterpart.

		+ 25% diesel price	+ 50% diesel price
€600 / kWh battery price	Similar kWh price	- 2.5	- 6.8
	- 25% kWh price	- 4.5	- 9.0
€400 / kWh battery price	Similar kWh price	- 4.8	- 9.3
	- 25% kWh price	- 6.9	- 11.4

Table 6: Extra TCO battery-electric fleet in million euros compared to diesel AGVs; a positive value indicates a higher TCO, a negative value a lower TCO

V. CONCLUSION AND FUTURE WORK

In this study, the operational and financial feasibility of replacing diesel AGVs by a battery-electric AGV fleet at brownfield container terminals has been evaluated by means of simulation and a total costs of ownership (TCO) analysis. To guarantee practical relevance of the results, the northern side of the ECT Delta Terminal at Maasvlakte 1 in Rotterdam, the largest terminal operator of Europe, has been chosen as a case from which corresponding operational and financial data have been obtained. With a focus on designing the charging process for battery-electric AGVs, *opportunity plug-in charging at the ASC transfer points* turned out to be the most promising design to be implemented at brownfield terminals based on terminal operator's design requirements and constraints and the AGV activity patterns on the terminal. The main findings indicate that battery-electric AGVs charged by means of this design prove to be an operationally and financially feasible alternative to diesel AGVs. By varying the number of battery-electric vehicles, battery capacity, charging power and number of charging spots, variables which are believed to be of influence on the operational and financial viability of electric vehicle deployment in closed transportation systems, it was found that with a sufficient amount of AGVs – a 15% increase of the current diesel AGV fleet size -, charging power and charging spots operational feasibility in terms of deep sea vessel turnaround times, QC productivity and QC utilization rate is ensured. Battery capacity tends not to correlate with terminal performance due to the high AGV idle and waiting times within a transport cycle, which provide enough time for the AGV to charge its battery to a sufficient level. Regarding the financial performance of battery-electric AGVs, the results indicate that especially future increases in diesel price could result in a positive TCO for this AGV type compared to diesel AGVs. This is explained by the fact that, unlike AGV maintenance costs, improvement in operational expenditures is mostly made by the reduction in fueling costs, which cause around 25% of the TCO of diesel AGVs while only 6% of the battery-electric AGVs' lifetime costs. With this in mind, it can easily be reasoned that especially the diesel price is a decisive factor in determining the financial feasibility of battery-electric AGVs when compared to diesel AGVs rather than the electricity price.

As environmental legislation for heavy-duty vehicles becomes more stringent while there is a decreasing trend in electricity prices, battery-electric AGVs are most likely to become profitable for deployment at brownfield container terminals. This profitability is enforced by the reduction in local emissions and by the expected decrease of battery-electric AGVs' and chargers' purchase prices in case of large scale production. Therefore, this study's findings could pave the way for terminal operators to replace their environmentally unfriendly diesel AGVs by locally zero-emission vehicles, potentially becoming the key force increasing the global penetration rate of electric vehicles in heavy-duty industry.

This study contributes to the current state of scientific literature and industry's knowledge as, to the author's knowledge, no research has been conducted yet on the operational and financial feasibility of replacing diesel AGVs by battery-electric AGVs at brownfield container terminals. Since diesel-powered AGVs are almost exclusively used at brownfield container terminals characterized by an existing terminal layout and space constraints for new-to-be-installed charging infrastructure, previous studies on the financial feasibility of replacing diesel AGVs by electric AGVs charged by large battery swapping stations are most likely to be of less use for brownfield terminal operators' diesel AGV replacement programs [11][18]. Taking these spatial and operational constraints explicitly into account in this study's design and evaluation of the AGV charging process, brownfield operators are provided a more realistic way of replacing their current diesel AGVs by zero-emission vehicles.

Although this study adds to the understanding of the feasibility of implementing an electric AGV fleet at brownfield container terminals, the performed simulation study and TCO analysis also have limitations. First, physical interactions between AGVs have been left out of the simulation model; instead, a fixed average AGV speed has been applied which accounts for vehicle interactions on the way. However, when battery-electric AGVs will be opportunity charged at the ASC transfer points, the vehicle density – and thus the number of crossings – will increase at these locations. Consequently, the simulation may overestimate the operational feasibility of deploying battery-electric AGVs as no potential increase in congestion has been incorporated. Further research could thus incorporate vehicle interactions and investigate whether this has a significant effect on the results of the operational feasibility analysis. Second, the developed simulation model incorporated both busy and non-busy periods in terms of container arrivals to resemble real-world terminal performance as much as possible. Consequently, the corresponding required number of battery-electric AGVs obtained from this study is directly related to the average over both these busy and non-busy periods. Since terminal operators purchase AGVs according to the demand during peak hours, it might be interesting for further research to study the required battery-electric fleet size for these moments only. Finally, this study has left out the net present value of costs from the TCO analysis. As was deducted from the results, a battery-electric AGV fleet largely becomes financially feasible over diesel AGVs due to the reduction in fueling costs over an AGV's lifetime. When accounting for this *time value of cash*, it is expected that the financial viability will significantly be reduced as fueling cost reductions weigh less heavily over the years while the weight of initial investment costs in batteries and charging infrastructure remains the same. Further research could thus include this net present costs principle in order to investigate whether, and more important under what conditions, a battery-electric fleet becomes financially viable over diesel AGVs.

As a final remark, this study explicitly considered container terminals as closed transportation system in which electric vehicles are deployed. Further research could extend the findings mentioned in this paper to other closed transport systems, such as distribution centers and airports, in order to gain a better understanding of the operational and financial challenge the industry currently is facing regarding the trend towards sustainability.

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