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

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***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in formal legislation and market developments towards sustainability, these diesel AGVs are most likely to become outdated.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

[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.

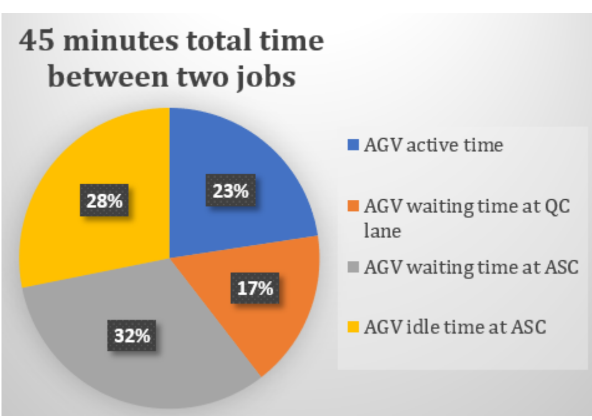

Figure 1: AGV active, waiting and idle time distribution

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].

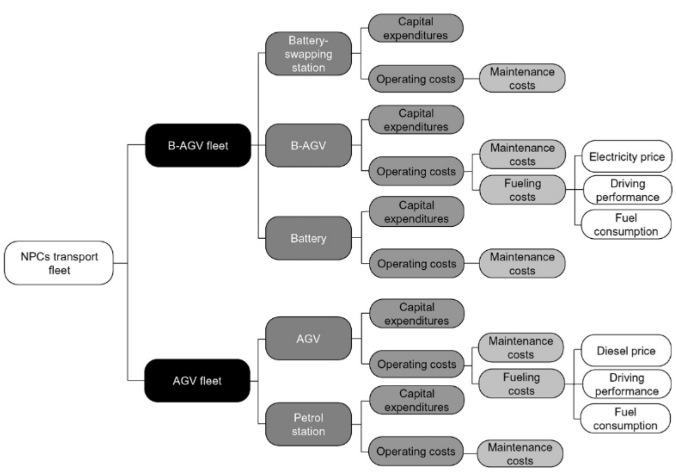

Figure 3: Cost elements framework of Schmidt et al [11]

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.

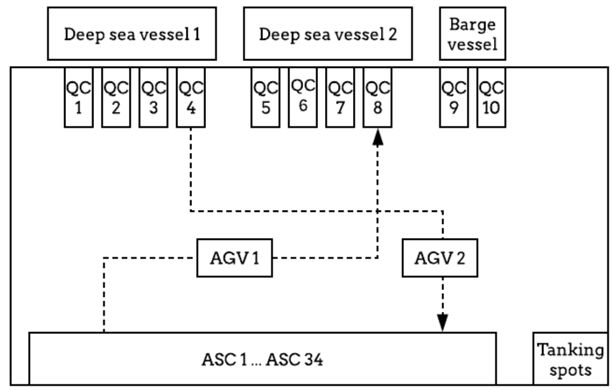

Figure 4: Terminal and equipment configuration of the DDN implemented in the simulation model

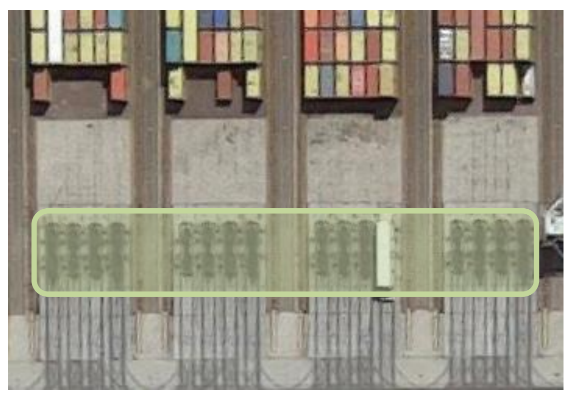

Figure 5: Potential charging spots at the ASC transfer points highlighted in green

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.

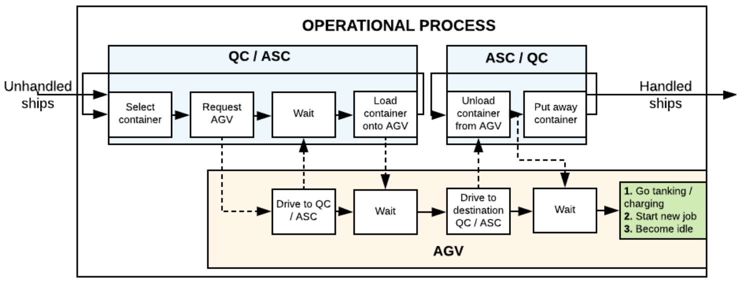

Figure 6: Structure of the operational process implemented in the simulation model

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.

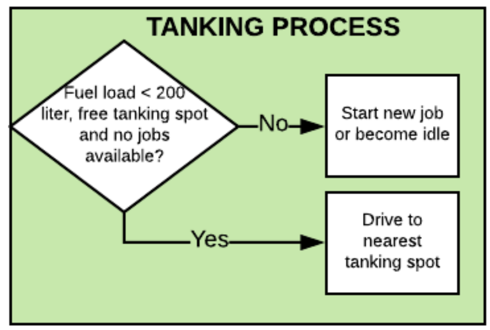

Figure 7: Implemented AGV tanking logic

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.

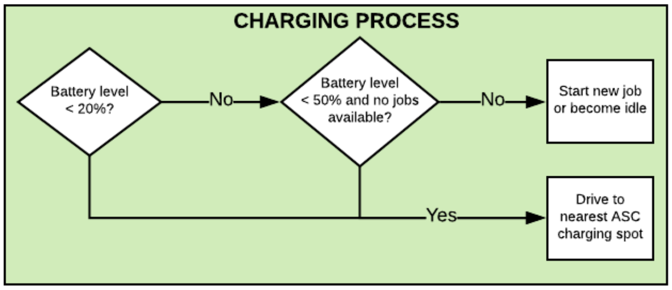

Figure 8: Implemented AGV charging logic

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:

$$t_{charge}\,[h] = \frac{0-80\%\;of\;capacity\;[kWh]}{charging\;power\;[kW]*\eta} + \frac{80-100\%\;of\;capacity\;[kWh]}{\frac{1}{4}*charging\;power\;[kW]*\eta}$$

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

[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.

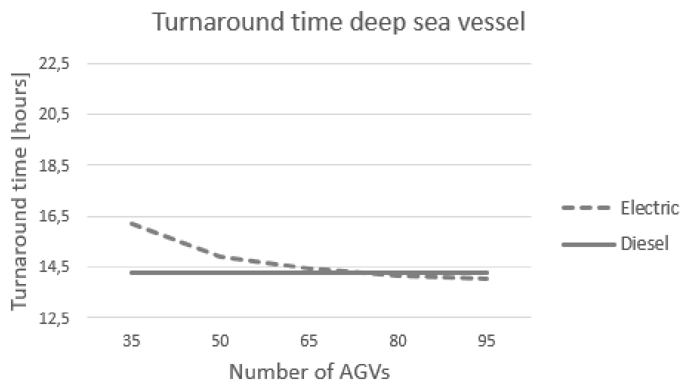

Figure 9: Influence of varying amount of battery-electric AGVs on operational performance

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.

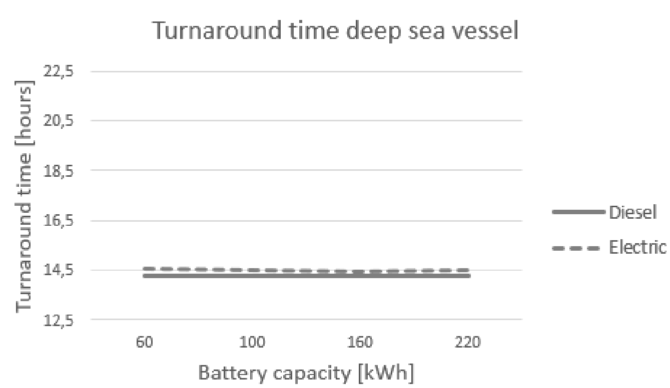

Figure 10: Influence of various battery capacities on operational performance

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.

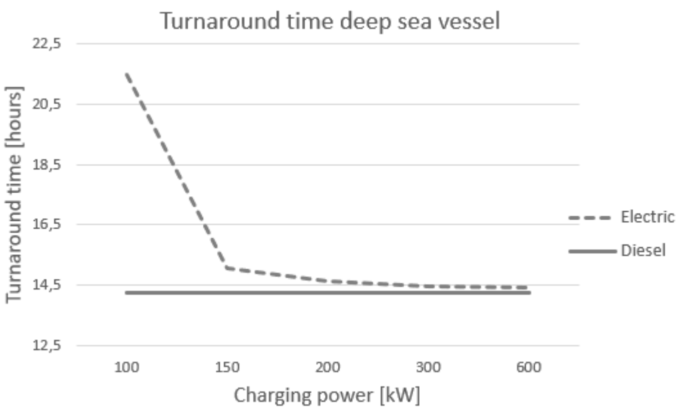

Figure 11: Influence of various charging power on operational performance

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.

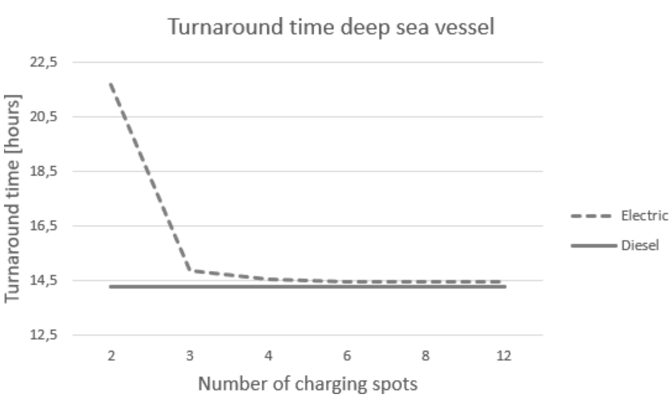

Figure 12: Influence of varying amount of chargers on operational performance

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.

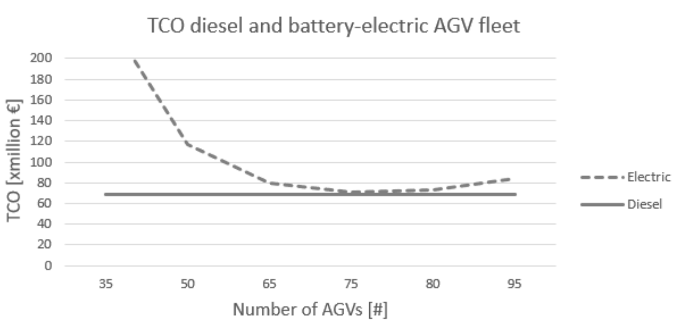

Figure 13: Influence of varying amount of AGVs on TCO of battery-electric fleet

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.

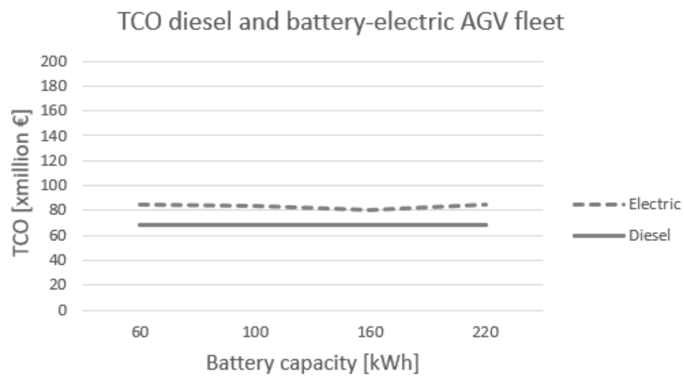

Figure 14: Influence of various battery capacities on TCO of battery-electric fleet

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.

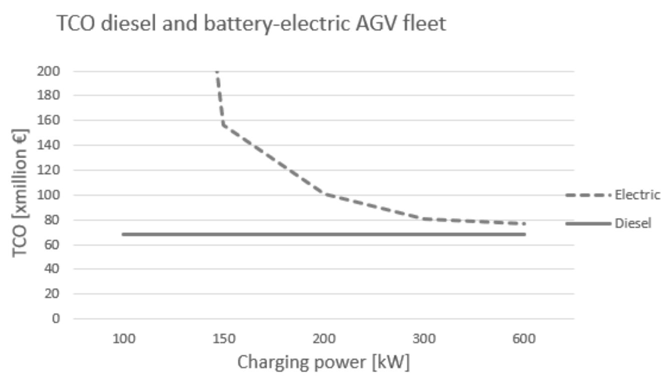

Figure 15: Influence of various charging power on TCO of battery-electric fleet

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.

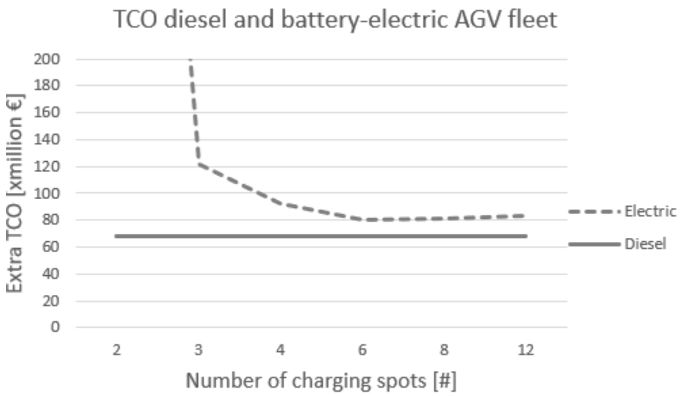

Figure 16: Influence of varying amount of chargers on TCO of battery-electric fleet

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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