Green vehicle technology to enhance the performance of a European port: a simulation model with a cost-benefit approach

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Abstract

In this paper, we study the impact of using a new intelligent vehicle technology on the performance and total cost of a European port, in comparison with existing vehicle systems like trucks. Intelligent autonomous vehicles (IAVs) are a new type of automated guided vehicles (AGVs) with better maneuverability and a special ability to pick up/drop off containers by themselves. To identify the most economical fleet size for each type of vehicle to satisfy the port's performance target, and also to compare their impact on the performance/cost of container terminals, we developed a discrete-event simulation model to simulate all port activities in micro-level (low-level) details. We also developed a cost model to investigate the present values of using two types of vehicle, given the identified fleet size. Results of using the different types of vehicles

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are then compared based on the given performance measures such as the quay crane net moves per hour and average total discharging/loading time at berth. Besides successfully identifying the optimal fleet size for each type of vehicle, simulation results reveal two findings: first, even when not utilising their ability to pick up/drop off containers, the IAVs still have similar efficacy to regular trucks thanks to their better maneuverability. Second, enabling IAVs' ability to pick up/drop off containers significantly improves the port performance. Given the best configuration and fleet size as identified by the simulation, we use the developed cost model to estimate the total cost needed for each type of vehicle to meet the performance target. Finally, we study the performance of the case study port with advanced real-time vehicle dispatching/scheduling and container placement strategies. This study reveals that the case study port can greatly benefit from upgrading its current vehicle dispatching/scheduling strategy to a more advanced one.

Keywords: Discrete-event simulation, fleet sizing, intelligent autonomous vehicles, automated guided vehicles, container terminals, cost-benefit analysis

1. Introduction

Container terminals play a vital role in international supply chains, since container terminals are major interfaces to transfer/distribute containers (carrying 90% of non-bulk world trade goods as of 2009 (Ebeling, 2009)). How container terminals handle goods greatly influences emissions and final cost, because up to 50% of cost could be due to handling and logistics (Rodrigue et al., 2013, Chapter 5). Thus, improving container terminals efficiency is an important/practical issue (Ha et al., 2007). The growth in the global container market has made container terminals key hubs of global supply chain networks (Xin et al., 2014). Therefore, if a container terminal wants to be successful in this market, it should improve its performance and also be able to keep its operational costs at the lowest level (Soriguera et al., 2006). Moreover, with the growth of containerisation, container terminals have to face with the problems of limited space (Gambardella et al., 1998). Some container terminals, especially European ports, have difficulties to cope with congestions caused by the increase in equipment and activities in ports. Due to the limited available land, it is not possible to increase the area of container terminals despite the needs in increasing capacity (Henesey et al., 2006). Thus, the capability of equipment to perform in confined spaces has become an advantage.

Due to the aforementioned issues, container terminals have been looking for new technologies to improve their performance. The first step is to identify the most suitable sets of equipment. However, since the introduction of containers in 1960, identifying the optimal amount of equipment and capacity of container terminals has always been a challenging task due to the complex nature of the problem. One possible way to solve this challenging task is to use simulation. Simulation is a scientific approach to not only study a system without actually disturbing it (Demirci, 2003), but also to evaluate concepts that have not been used in the real world (Henesey et al., 2006; Yun and Choi, 1999). Therefore, for a container terminal, a simulation study can be carried out to predict the effect of applying different types of equipment, as well as the ideal amount of equipment to meet the performance target (Ha et al., 2007; Yun and Choi, 1999; Parola and Sciomachen, 2005; Bielli et al., 2006). This is the focus of this paper.

In this paper, we develop a simulation model to identify the optimal fleet size in terms of cost and performance to assist investment decisions for a European container terminal. We also investigate the impact of using a new type of automated vehicle called intelligent autonomous vehicles (IAVs) in comparison with trucks on the performance and cost in this terminal. Automated vehicles have been used in container terminals before. The most commonly used of automated vehicles are the automated guided vehicles (AGVs) which have been used in many European ports. The current generation of AGVs, however, have two limitations. First, they cannot pick up/drop off containers by themselves, resulting in increased expensive crane/vessel waiting time. Second, many of them need to follow a fixed track, which can be either a pre-programmed virtual path or a physical part guided by transponders. The purpose of the development of the IAVs (and similar vehicles, e.g. the IPSI AGV (Henesey et al., 2006) and automated lifting vehicle (ALV) (Vis et al., 2005)) is to partly alleviate these limitations. IAVs are a new type of AGV. They are developed in a European project entitled Intelligent Transport for Dynamic Environment (InTraDE)[2]. IAVs are used to transport containers in container terminals. Below, we provide some key technical features of IAVs:

- IAVs have the ability to pick up/drop off containers by themselves if they are combined with a special table-shaped object named "cassette".
- IAVs offer flexibility in maneuvering in confined spaces (can move in any directions without having to turn thanks to 180-degree-rotation wheels).
- IAVs do not need any fixed track to follow. This is achieved thanks to the wireless link between the IAV and an intelligent virtual real-time simulator.
- An IAV benefits from an embedded sensor system to detect moving and static obstacles around itself. Thanks to this system an IAV can track targets with an accuracy of a centimetre.
- IAVs contain a global positioning system coupled with simultaneous local-

[2] See http://www.intrade-nwe.eu/

isation and mapping technology for navigation.

- An IAV contains eight full electrical and decentralised actuators, four for traction and four for steering. If an actuator fails, the IAV can still continue its assigned job, given that the rest of actuators can cover the failed actuator.

- IAVs can make platoons in which each IAV can follow one another and form a train of IAVs. The platoon can be led by a leader (usually a man driven vehicle).

The first two features of IAVs in the above list are the main focus of this paper. The ability to pick up and drop off containers is significant in improving performance because it helps reduce waiting time of vehicles and cranes. Instead of having to wait for vehicles to arrive, cranes can now drop off containers on top of an empty cassette, then continue picking up another container. The loaded cassette then can be picked up by the IAV at a later time. Similarly, when an IAV arrives, it no longer has to wait for a crane to give it the container. Instead, the IAV can go directly to one of the loaded cassettes, pick it up and transfer it to the destination. IAVs can also drop off the loaded cassettes on the ground for cranes to pick up later. The temporary space for the storage and transition of empty and loaded cassettes is called the buffer. By utilising the buffers, the waiting time of both cranes and vehicles can be decreased significantly. This can have a significant impact on the productivity and cost of container terminals[3]. Moreover, IAVs' better maneuverability can potentially shorten their travel routes. This can be achieved in confined places where trucks cannot turn due to the lack of enough space and hence have to take the long round routes.

[3] A video illustrating how the IAVs work can be found in [https://www.youtube.com/watch?v=49vqrl1O0N8].

In contrast, IAVs could move in any directions without having to turn, hence can choose the shortest routes.

It should be noted that IAVs, IPSI AGVs and ALVs belong to the same modern class of automated vehicles that are able to pick up/drop-off containers by themselves. This is an emerging technology that requires in-depth studies to investigate its strengths/weaknesses in a wide range of different container terminals. This paper is one of such studies. In this paper, we are not trying to prove that the IAV technology is different from IPSI AGVs or ALVs, but to contribute some novel methodologies to the study of whether and how this emerging class of automated vehicle can improve performance in container terminals. Below we will show the significance, timeliness and novelty of this paper.

Regarding significance and timeliness, although the technologies behind IPSI AGVs and ALVs have been introduced in the academia for some years, they have not been properly introduced to the wider audience. This is because there have been very few papers studying the benefits of these types of vehicle (only 8 journal papers Le et al. (2012); Nguyen and Kim (2009); Bae et al. (2011); Duinkerken et al. (2006); Vis and Harika (2004); Vis et al. (2005); Ranau (2011); Yang et al. (2004) according to (Angeloudis and Bell, 2011; Carlo et al., 2014b; Vis and De Koster, 2003)). Thus, we believe that there is a great potential to conduct in-depth research on this topic to further promote these emerging technologies. We hope that the contribution of this paper and similar papers in the literature will enable these types of vehicle to be more common in the future.

Regarding novelty, the proposed methodology in this paper is also totally different from the existing research in the literature. As reviewed in (Angeloudis and Bell, 2011; Carlo et al., 2014b; Vis and De Koster, 2003), most existing research on IPSI AGVs, ALVs just focus on either just simulation or just one optimisation method. They also either did not provide a cost model or provided a cost model with no reproducible details.

This paper attempts to fill the above gap. It provides for the first time an integration of various recent algorithms and simulation tools to offer better insights into how different advanced methods can be combined to improve the performance of container terminals. This integration of tools can be applied to not only IAVs but also other types of vehicles in ports such as IPSI AGVs, ALVs, AGVs, straddle carriers, shuttle carriers and trucks. This paper also provides for the first time a detailed cost model for evaluation of IAVs. This cost model was verified by real data from the case study container terminal.

The contribution of this paper can be summarised as follows. First, a comprehensive literature review on simulation studies in container terminals was provided. Second, a high-fidelity simulation was developed using real data to investigate the performance of the case study container terminal with IAVs compared with the current vehicle system (i.e. trucks). This is the first research of this kind for IAVs. Third, the FlexSim CT simulation software was extended to be able to accommodate IAVs and similar vehicles such as IPSI AGVs and ALVs. Fourth, a detailed cost model was developed to estimate the total cost of the case study container terminal with IAVs and trucks. Different parameters that are related to the IAV and truck capital and also their operational cost were identified and included in the cost model. The cost model was then verified with real data from the case study container terminal. Finally, detailed analyses on the applications of different online vehicle scheduling algorithms and container placement strategies in a small-medium port were provided.

This paper is structured as follows. Section 2 reviews relevant simulation studies in container terminals. Section 3 describes our developed simulation model to investigate how IAVs can be accommodated in container terminals and whether they can contribute to the improvement of performance of container terminals. All the specifications and settings of the model are explained in this section. Section 4 discusses the results of the simulation study. We first explain the chosen performance measures to evaluate the results of using trucks and IAVs to identify the optimal fleet size of IAVs and trucks. We then provide the results of the cost model based on the given optimal fleet size. Section 5 studies the performance of the case study port with advanced vehicle dispatching/scheduling and container placement strategies. Finally, Section 6 concludes this paper.

2. Literature review

The decision making and optimisation problems in container terminals can be tackled generally by either analytical or simulation approaches (Steenken et al., 2004; Stahlbock and Voß, 2008). A container terminal, however, is a complex system and developing an analytical model that can incorporate all the relations between the objects and considering all the operation details would be very difficult and sometimes impossible. In contrast, discrete-event simulation can be used as an alternative tool for the study of a complex system like container terminals (Parola and Sciomachen, 2005). In this section, we briefly review the relevant research that used simulation models to study the performance of container terminals. For an intensive literature review on the simulation studies in container terminals, readers are referred to (Angeloudis and Bell, 2011). In this survey, the papers were categorized and reviewed based on three factors: the case studies, the purpose of simulation and properties of simulation models.

The impact of buffers of containers on the performance of container terminals was studied in (Henesey et al., 2006; Vis and Harika, 2004). In (Henesey et al., 2006), a simulation model using the DESMO-J library was developed to evaluate an improved AGV system named IPSI AGV. The authors followed an agent based approach in which quay cranes, cassettes, containers and AGVs were considered to be the agents of this simulation model, each with specific attributes and functions. Using realistic data (not specified), sensitivity analysis was conducted to identify the optimal number of quay cranes, AGVs and cassettes to minimise the container handling rate and maximise terminal equipment utilisation rate. This simulation, however, did not consider the cost factor of using IPSI AGV.

In (Vis and Harika, 2004), the authors compared two different types of automatic vehicles, namely AGVs and ALVs using the Arena simulation software. An ALV benefits from the lifting ability by which it can pick up/drop off containers by itself from/to the ground and hence utilises buffers of containers under cranes. The authors provided comparisons between the optimal number of AGVs and ALVs by comparing the total discharging time of a vessel as a measure. Results showed that the optimal number of ALVs is smaller than that of AGVs. The authors then compared the purchasing cost of the optimal numbers of AGVs and ALVs.

The IAV is a very new type of AGVs in container ports and thus very few studies have been conducted on it. The followings are two relevant papers on IAVs. Gelareh et al. (2013) developed a Lagrangian relaxation-based decomposition algorithm to schedule IAVs in container terminals. In this algorithm, the pairing feature of IAVs was taken into account by which two 1-TEU (20-foot Equivalent Unit) IAVs can make a dynamic joint to be able to carry together a container with any size between 1-TEU and 1-FFE (40-foot Equivalent). The output of the algorithm was simulated using simulation. Another research on IAVs was conducted by Dong et al. (2011) to discuss ideas of how a decision support system for IAV-based container ports can be provided. The authors discussed different heuristics for IAV-related decision-making problems such as the quay crane scheduling, IAVs and cassettes allocation, container storage allocation, dispatching and routing of IAVs.

In (Veenstra and Lang, 2004), a simulation model was developed to provide an economic analysis on a container terminal. A typical container terminal similar to the Delta container terminal in Rotterdam was modelled using the DSOL library in Java which consists of environments and transformation systems. The simulation model was combined with an economic appraisal model to analyse the performance of the container terminal with respect to some economic factors such as the investment policy, cost structure, income structure and net cash flow. The authors claimed that their economical approach is not limited only to container terminals and can be extended to any logistic systems. The economic appraisal model was a spreadsheet to calculate the financial figures using the results of the simulation for long term periods. Detailed simulation input data such as the number of automated stacking cranes (ASCs), number of AGVs and other specifications of the container terminal were provided. However, the paper does not provide any detail of the economic appraisal model. The authors also had difficulties in the integration of operational and economic simulation models due to the differences in the ways the two models deal with time. The operational simulation model is event based while the economic simulation is time-step based. To overcome this issue, the author proposed an approach to integrate the two simulation models by aggregation over objects and de-aggregation over time.

In (Bielli et al., 2006), a distributed discrete event simulator for container terminals using the Java programming language was developed. Using the unified modelling language diagrams, relations between different entities of the simulator and the way events are managed were explained. The authors also provided very informative details regarding the operations of equipment in container terminals and also compared the existing equipment. The simulator was then applied to realistic data from Casablanca container terminal in Morocco. The authors used a cost model to evaluate the performance of the container terminal under study. However, details of such a cost model were not provided. In addition, the authors did not reveal the configurations and settings of the container terminal under study.

In (Cortes et al., 2007), the Seville inland port was simulated using the Arena simulation software. Spatial movements were not considered in this simulation. This port consists of three docks. Vessels can access the port through the Guadalquivir estuary and a lock by which the river is connected to a harbour. The port can deal with different types of cargo and each type of cargo is handled differently in a specific dock and berth. The simulation model was explained in detail by providing the detailed simulation modules such as vessel arrivals, dock assignment, vessel departure and lorry arrivals modules in addition to modules regarding the handling of each specific type of cargo in the docks. Using the given performance measures such as containers per hour and tons per hour the traffic flow of the port was analysed.

Douma et al. (2009) looked into the problem of alignment of barge rotations (i.e. the sequence of vising different terminals) with quay schedules in the port of Rotterdam. The authors developed an agent-based simulation approach in which the terminal and barge formed the agents of this simulation. The agents in this model can communicate directly with each other to exchange information and make decisions based on the provided information. The results were compared with an off-line benchmark based on an optimisation algorithm.

A simulation model was developed in (Demirci, 2003) using the AweSim computer simulation language to identify the bottlenecks in the Trabzon port in Turkey. The simulation model was based on realistic data which were provided in detail. To identify the bottlenecks, in addition to the existing state of the port, a situation with the full capacity of the port was also considered. In the full-capacity situation, loading/discharging vehicles were considered to be the bottlenecks which can have a significant impact on the performance of the port. In this port, due to investment limitations only a limited number of vehicles could be added to the fleet. This situation was investigated in the simulation. The results showed that the performance of the port was enhanced with the additional vehicles.

Kia et al. (2002) compared the current layout of an Australian port with their newly proposed layout using a simulation model. In the proposed model, a ship-to-rail direct loading approach was considered to move the containers directly from the berth to a distribution centre by trains. Results showed that using the proposed method the total occupancy of berth/yard was decreased compared with the current conventional method.

The Plant simulation package was used in (Ha et al., 2007) as a simulation tool to simulate a hypothetical container terminal which uses AGVs. Two sets of objects were considered in this simulation: material flow (MF) objects and moving unit (MU) objects. The authors considered quay cranes, yard cranes transporters, external trucks, container vessels and containers to be MU. The MF objects are the objects that generate, destroy and route the aforementioned MU objects. AGVs motions were represented using virtual tracks in the simulation. By considering the berth productivity as the performance measure, the optimal settings, i.e. the number and specifications of equipment, were identified following a sensitivity analysis.

Vaněk et al. (2013) developed an agent-based model for the maritime traffic simulation. In this model, the authors focused on pirate activities and piracy countermeasures. The what-if analysis approach was followed to simulate different real-world scenarios. Baird and Rother (2013) provided economic evaluation of a floating container storage and transhipment terminal. The capital and operating costs of this system were estimated and the cash flow was foretasted based on the traffic volumes.

In (Liu et al., 2002), the authors compared four different types of equipment in an automatic container terminal. The four sets of equipment are automated guided vehicles, a linear motor conveyance system, an overhead grid rail system and a high-rise automated storage and retrieval structure. The authors developed a simulation model and used a cost model from the literature to compare the four equipment based on the average cost per container (calculated using the cost model). The results showed that with automated guided vehicles the automated container terminal can achieve the least average cost per container. Liu et al. (2004) compared the performance of the Norfolk terminal with two proposed layouts for AGVs using simulation models. The simulation was developed using the Matlab software. A control logic to prevent deadlocks and collisions was included in the simulation. A simple additive weighting method was used to evaluate the performance of the container terminal given different measures such as average waiting rate of AGVs, average idle rate of AGVs, average stop rate of AGVs and total throughput of the container terminal. This method assigned a weight to each performance measure and by comparing the weighted value of each measure it identifies the optimal measure. The optimal measure was used to identify the best layout, given the results of the simulation.

Hartmann (2004) proposed an approach to generate scenarios that can be used in simulation studies and optimisation problems in container terminals. In the scenarios, deep see vessels, feeder ships, trains and trucks arrivals, and containers can be generated using the given parameters from users. The algorithm and input parameters to generate scenarios such as means of transportation (e.g. vessel, train and truck), arrival frequencies and container properties were explained in detail. The generated scenarios were validated with realistic data from the HHLA container terminal Burchardkai in Hamburg, Germany. The generated scenarios were used to study container stacking strategies in the HHLA container terminal Altenwerderin Hamburg, Germany using a simulation model. The simulation model was developed using the emPlant software package. Equipment such as quay crane, automated guided vehicles and stacking cranes were not modelled explicitly, but stacking strategies and stacking blocks were the main focus of the simulation. The results of the simulation, however, due to the confidentiality reason were not revealed.

As can be seen from the review above, the reviewed simulation studies are case-dependent and thus it is not possible to use a simulation model of one container terminal for another container terminal. Therefore, to analyse the scenarios of trucks versus IAVs in our case study container terminal, it is necessary to develop a new simulation model specifically for this terminal. In the next section, we will describe the details of such a model which we developed using a simulation software named FlexSim CT.

3. The simulation model

This section first provides a brief introduction to the Flexsim CT simulation software. We then explain the specifications of the developed simulation model to study the productivity of trucks and IAVs, as well as their optimal fleet sizes, in the case study port.

3.1. Flexsim simulation software

Flexsim CT is a purpose-built container terminal simulation tool to develop simulation models. Flexsim CT is an extension of the Flexsim general purpose software where it offers specific features for simulating container terminals such as the berth planner, quay cranes, stacking blocks and stacking cranes. The benefit of Flexsim and Flexsim CT is that, in addition to the standard discrete-event simulation features, they support good 3D visualisations, as well as the ability to rewrite some part of the source code (written in C).

3.2. The case study port and its layout

In this paper, we consider a small size container terminal in Europe to be the case study (let us call it port A)[4]. Figure 1 shows a snapshot of the simulation model with the map of port A as the background. It can be seen that port A has three quay cranes at berth, six blocks to stack importing containers and three blocks to stack export containers. Each of the stacking blocks is equipped with one rubber-tyred gantry crane to stack/unstack containers. The positions of quay-side and stack-side areas are shown in Figure 1.

"place Figure 1 about here"

In port A, trucks are currently being used to transport containers between the quay-side and stack-side areas. Trucks follow a loop-shaped layout between the quay-side and stack-side areas. It means that once a truck drops off/collects containers to/from a block, it will have to travel all the way to the end of the block, then take a long circle round the port to go back to the quay-side area (Figure 2). This is because trucks cannot turn in the narrow space inside the stacking areas.

[4]This container terminal has committed to considering the results of this paper to enhance their operations. Due the confidential agreements with this container terminal we cannot reveal its identity.

"place Figure 2 about here"

Different from trucks, IAVs are better at maneuvering in confined places thanks to their novel 180-degree-rotatiton wheels. The wheels allow them to move in any direction, including moving forward, backward and sideways without having to turn. It means that, in port A, once an IAV has picked up/ dropped off a container along a block, it can reversely go back to the quay-side using the same route without having to take a long circle like the trucks, or it can change direction at any point (Figure 3). Thus, to do the same job in the same container terminal, an IAV has a significant less travel distance than a truck. This potentially leads to time and money savings.

"place Figure 3 about here"

3.3. Berth configuration

We simulate the berths' layouts using real-world data as in Figure 1. Following real-data, we simulated weekly transactions of port A, of which the busiest transactions has about 300 containers to be discharged from the vessels and 300 containers to be loaded to the vessels. Containers were assumed to be distributed evenly between the quay cranes and import/export blocks.

3.4. Quay and stacking cranes

Based on real data from this container terminal, the cycle time of each quay crane was considered two minutes, i.e., it takes averagely two minutes for a quay crane to locate a container, pick it up and then place it on top of a vehicle, an empty cassette or a vessel. Based on the real data, the cycle time for a stack crane to stack/unstack a container was considered to be averagely 3.5 minutes. We simulated the container placement strategy that is currently being used in port A: keeping container stacks at the lowest height possible i.e. the number of containers that are stacked on top of each other should always be minimal. This strategy was called “Levelling” in Duinkerken et al. (2001). This strategy attempts to reduce the number of container re-locations by keeping the number of containers that are stacked on top of other containers as minimum as possible. This strategy has another advantage: the minimum height minimises the risk of containers being tipped over. As one can see, this container placement strategy considers the number of stacked containers as the only criterion to stack a container. However, there are other important factors that a container placement strategy should take into consideration to effectively reduce the number of unproductive crane moves (Lin et al., 2015). In Section 5, we study the performance of port A with a recent and more advanced container placement strategy.Vehicles

To investigate the difference in port productivity using IAVs against trucks, two simulation models were developed: one for trucks and one for IAVs. There are two main differences between the simulation models. The first difference is the travel routes. As mentioned in subsection 3.2, IAVs’ better maneuverability help them to travel shorter distances (compared with trucks) to carry out the same task (Figure 3), so the two simulations have two different travel routes. The second difference is the (in)ability of vehicles to pick up/drop off containers. IAVs can pick up/drop off containers by themselves when being combined with the cassettes while trucks cannot do so.

The current version of Flexsim CT supports only two types of transfer vehicles: truck and straddle carrier (a vehicle able to top-lift containers and stack them to a container block without the need of a stacking crane). Flexsim CT does not support IAVs or any similar type of vehicles. It means that we need to create a new vehicle object for the IAV in Flexsim CT.

We did so by modifying the straddle carrier, the vehicle that is somewhat similar to an IAV in the sense that it can also pick up and drop off containers. However, there are some significant issues, resulting from the differences between a Flexsim CT's straddle carrier (CTSC) and an IAV: 1) the appearances of two vehicles are very different; 2) CTSC can only pick up/drop off containers from/to the ground in the quay side while IAVs need to pick up/drop off containers in both quay side and stack side; 3) CTSC does not work with stack cranes - they can stack containers to the storage blocks by themselves. On the contrary, IAVs need to work with stack cranes - they can only deliver containers to the ground next to a container block, and then the crane in that block will do the stacking.

To overcome the first issue, difference in appearances, in the simulation we just simply replace the 3D image of a straddle carrier with that of an IAV. To overcome the second and third issues, we combine the straddle carrier object with another Flexsim CT object - the transfer area. In Flexsim CT, a transfer area is a waiting area dedicated to truck-like vehicles to wait before being served by stacking cranes (Figure 4).

"place Figure 4 about here"

For the purpose of overcoming the two aforementioned issues, we use transfer areas for a different purpose: to connect CTSCs with stack cranes. We do so by placing a transfer area next to each container block, which in turn is served by one stack crane. As mentioned previously, CTSCs do not work with stack cranes because CTSCs can stack containers in blocks directly without the cranes. However, CTSCs do work with transfer areas because transfer areas can be considered special blocks of containers. So, we can make CTSCs and stack cranes working together by asking CTSC to bring containers to transfer areas, then asking stack cranes to pick up those containers from the transfer areas and stack them to the blocks (Figure 5). This way, we resolve issue 3.

Because we place transfer areas in the stack areas, we make it possible for

CTSCs to pick up/drop off containers in the stack side. This resolves issue 2.

By modifying the existing straddle carrier object and adding the transfer object, we resolve all the three issues and make a CTSC work exactly like an IAV, i.e. to pick up containers from a buffer in the quay side, then bring them to another buffer in the stack side and vice versa. It means we can use a CTSC to represent an IAV. Similarly, we can use a transfer area to represent a buffer for cassettes in the stack side. Note that in the quay side we do not need to use transfer area to represent a buffer because CTSC does support pick up/drop off containers from/to the ground on quay side by default, i.e. CTSC have their own buffer on quay side by default.

Figures 5 and 6 show how all the modified objects work together to simulate the behaviour of IAVs and cassettes in the port.

"place Figure 5 about here"

"place Figure 6 about here"

3.5. Vehicles' speed and dispatching strategy

In this paper, for both IAVs and trucks we considered the same realistic Weight-based Dispatching Strategy (WDS) that is currently being used in port A. WDS assigns a job (i.e. a container) to a vehicle based on the following criteria: 1) the distance from the vehicle to the container; 2) the workload of the crane from which the job is originated; and 3) the maximum number of vehicles that can be assigned to a crane. The first criterion is to reduce the empty travel time of vehicles. The second criterion is to adjust the number of vehicles assigned to cranes according to cranes' workload (defined as the number of remaining containers that a crane needs to process). The busier cranes obviously require more vehicles, but the number of vehicles assigned to each crane should be limited to a certain level; otherwise there could be a long queue of vehicles

Algorithm 1 Weight-based Dispatching Strategy (WDS)

1: $bestScore := 0$
2: $bestCrane := 0$
3: **for** i **from** 1 **to** $craneNo$
4: $\quad score := 0$
5: $\quad$ **if** the number of vehicles assigned to crane i has reached the upper bound u
6: $\quad\quad$ **continue**
7: $\quad$ **if** crane i has any container that has not been assigned to a vehicle
8: $\quad\quad score := w_d * distance(v, i)$
9: $\quad\quad score += w_c * r_i$
10: $\quad$ **if** $(score > bestScore)$
11: $\quad\quad bestScore := score$
12: $\quad\quad bestCrane := i$
13: **if** $bestScore = 0$ (i.e. there is no more upcoming container)
14: $\quad$ dispatch vehicle v to the waiting depot
15: **else** dispatch vehicle v to crane $bestCrane$

where v is the vehicle to dispatch, $craneNo$ is the number of cranes, $distance(v, i)$ is the function to calculate the distance between vehicle v and crane i, w_d is the weight of the distance between vehicles and cranes, r_i is the number of remaining containers for crane i, w_c is the weight of r_i, and u is the maximum number of vehicles that is allowed to assign to a crane.

waiting next to the busier cranes. This limit is represented by the third criterion. There is a weighting value associated with the first and second criteria. By tuning these weighting values, we can achieve an acceptable distribution of vehicles between the cranes. Algorithm 1 sets out the pseudo-code for WDS used in this paper. Note that the dispatching strategy in Algorithm 1 is similar to the strategies used in Briskorn et al. (2006) and Hartmann (2004).

In line 14 of Algorithm 1, if there is no job for vehicle v to be assigned to, the vehicle will be sent to the waiting depot as shown in Figure 1. Once new jobs become available, the vehicles at the depot will be dispatched based on WDS. It should be noted that in the literature there are more sophisticated strategies for vehicle dispatching [5]. However, we will use WDS in this section, since it is

[5] For a recent review on the vehicle dispatching strategies in container terminals, readers are referred to Carlo et al. (2014b).

currently being used in port A. To investigate the impact of a more advanced online dispatching/scheduling on the performance of port A, in Section 5 we will also implement one of such advanced scheduling algorithms in the simulation of port A and carry out performance analyses.

Table 1 shows the speeds and acceleration of vehicles. It can be seen that the speeds of trucks (from real-world data in the port) are significantly higher than the speeds of IAVs (hypothetical, worst-case scenario values). Note that IAVs actually can move much faster than the values used in this paper. However, since IAVs have not been implemented commercially yet we only consider the worst-case scenario with the lower bounds for the IAV speeds.

"place Table 1 about here"

4. Experimental studies

In this section, we first compare results of the simulation models of the terminal in two cases: using trucks and using IAVs without cassettes (i.e. IAVs do not pick up/drop off containers by themselves). To do so, we follow a sensitivity analysis approach by varying the number of vehicles from 3 to 25 to investigate the performance of port A using these different numbers of IAVs and trucks. We then study the impact of using cassettes on the port performance by varying the size of the buffers (number of cassettes) from 1 to 10 and also varying the number of vehicles from 3 to 25. Finally, we use the results of the experiments to identify the optimal type and number of vehicles and also the size of the buffers for port A. To have a better understanding of the performance of port A, we report the results of discharging and loading separately. This is because the optimum number of vehicles for discharging and loading can be significantly different, given the differences between the number of import and export blocks and also the geographical positions of import and export blocks in regard to the quay-side area (Figure 1).

4.1. Performance measures

In container terminals, it is very important to minimise the total discharging/loading time, because vessels at ports are much more expensive than they are on the sea (Steenken et al., 2004). The total discharging/loading time at ports is highly dependent on the total loading/discharging time when containers are loaded/discharged to/from the vessel. The smaller the loading/discharging process time is, the shorter time the vessel has to stay. The total loading/discharging time, in turn, is dependent on the quay crane net moves per hour. This is because containers are discharged/loaded using quay cranes from/to vessels and hence the higher the quay crane moves per hour, the shorter total loading/discharging time. Therefore, we chose the quay crane net moves per hour as the performance measure for the simulated port. We then calculate the total discharging/loading time at berth given the quay crane net moves per hour. Using the total discharging/loading time at berth we identify the optimal number of vehicles.

4.2. Simulation validation

Before we can use the simulation model to study the impact of trucks and IAVs, we first need to validate it against historical data from the real environment (port A). In the validation phase, we ran the simulation using exactly the same settings as recorded in the port's historical data to see if we can simulate the same average productivity (average number of moves per hour) as recorded in historical data. We used the same fleet size of ten as currently being used in the port. In these experiments, the number of containers was varied from 100-300 and the number quay cranes was varied from 1-3 per transaction to cover almost all the possible realistic scenarios. The simulation produced an average quay crane net moves per hour of 24.1, which is close to the real-world value of 25 moves per hour as recorded by the port. This validation shows that the simulation is valid and accurate. It hence can be used to analyse the difference between trucks and IAVs, as will be shown in the next sections.

4.3. Experiment settings

Two simulation models were created for the experimental study, one for trucks and one for IAVs. Each model was run for 30 times and the average results of the 30 runs were reported. All the experiments were conducted on a 32-bit Intel(R) Core(TM)2 Duo 2.93 GHz with 3 GB RAM.

4.4. Trucks versus IAVs - without cassettes

In this subsection, we compare trucks and IAVs where no buffers for IAVs are considered. In other words, in this comparison we do not consider the ability of IAVs to pick up and drop off containers by themselves. Therefore, the main differences between IAVs and trucks in this comparison are: the different travel routes for IAVs and trucks (subsection 2) and different speeds of vehicles (Table 1).

Figure 7 shows the comparison results based on the crane net moves per hour. It can be seen that the performance of the two vehicles are quite similar. Obviously IAVs will give a much better performance if they are allowed to move faster. This suggests that the ability of IAVs to maneuver better can have a positive impact on the port performance. Figure 7 also shows that without the cassettes, both trucks and IAVs cannot increase the quay crane net moves per hour to more than 28 (i.e. no waiting time of quay cranes for vehicles) even when the fleet size is 25.

"place Figure 7 about here"

We use the results of Figure 7 to calculate the total discharging/loading time at berth. This measure is very important, since it shows how long vessels have to stay at the berth. To do so, we use the net moves per hour of the slowest quay crane and by considering the number of containers that are moved by that particular quay crane, the total discharging/loading time at berth can be calculated. Note that in the experiments, all quay cranes have to move roughly the same number of containers due to the way we distribute containers to cranes i.e. the total throughput of the quay cranes are equal (subsection 3.3). The calculation for the total discharging/loading time at berth is as follows:

Let:

q: number of quay cranes

m_i: net moves per hours for quay crane i, $1 \leq i \leq q$

n_l: total number of containers to be loaded

n_d: total number of containers to be discharged

s_l: average vessel loading time

s_d: average vessel discharging time

$$s_l = \frac{n_l/q}{min(m_1, ..., m_q)} \tag{4.1}$$

$$s_d = \frac{n_d/q}{min(m_1, ..., m_q)} \tag{4.2}$$

Using Equations 4.1 and 4.2, we calculated the total discharging/loading time for loading and discharging (Figure 8). It can be seen that by using IAVs without the cassettes, vessels can be served almost as in the same amount of time as by trucks in most of the cases. Note that in this experiment, the ability of IAVs to utilise buffers has not been considered. Given that IAVs are at a significant disadvantage due to their speed being severely restricted to be much slower than that of trucks, the fact that they still are able to get the same total discharging/loading time highlight the advantages of IAVs in being able to move in more flexible routes (Figure 3). Figure 8 also shows that there is a significant increase in the total discharging/loading time for IAVs against trucks where the number of vehicles is less than five. This is because when the number of vehicles is very small, the higher speed of trucks can compensate the shorter travel routes of IAVs. The other interesting finding about these results is: for the loading case (Figure 8-b) the total discharging/loading time at berth is not significantly affected by the number of vehicles. For example, the difference between the total discharging/loading time at berth for 25 vehicles and 6 vehicles is only 0.4 hours. This is because for the loading scenario the stack cranes are the bottlenecks due to two facts: (a) the vehicle travel time is short (due to the short distance between the quay side and the stack area used for loading a.k.a an export area), and (b) stack cranes are much slower than quay cranes. The combination of (a) and (b) means that once a vehicle has delivered a container to the quay crane and come back to the stack crane to get another one, it will have to wait because the stack crane has likely not finished picking up its next container yet. Because vehicles will likely have to wait for stack cranes regardless of how many vehicles are there, the fleet size does not play a major role in reducing loading time. To reduce loading time, the port operator would have to add more stack cranes, or use a more effective type of stack crane.

"place Figure 8 about here"

As can be seen in Figure 8, results of the loading case for trucks and IAVs are quite similar. However, for the discharging case, it is not very clear for each fleet size whether IAVs or trucks are significantly better. Thus, to provide better insights, we use the Mann-Whitney statistical test to investigate whether there is a significant difference between the results of trucks vs IAVs for each specific fleet size. We conducted this statistical test with a significance level of 95%. The results of the statistical test are shown in Table 2. This table shows whether IAVs or trucks can achieve a smaller discharging time. As can be seen in this table, in general when the fleet size is small (less than 11) IAVs are better while when the fleet size is large trucks are better.

Overall, it can be concluded that without using the cassettes, there is not much difference between using trucks or IAVs for port A. Although the IAVs' speed were set much slower than truck for safety reasons, their better maneuverability allows them to use shorter travel distances and hence achieve a similar performance. If IAVs are allowed to travel in a higher speed, they will probably achieve a better performance than trucks even without using the cassettes.

"place Table 2 about here"

4.5. Trucks vs IAVs with cassettes

In this subsection, we investigate the impact of utilising the buffers of containers with IAVs on the performance of port A. To save space, we only report the results of discharging tasks. This is because as explained in subsection 4.4, the impact of the optimal number of vehicles on the quay crane net moves per hour for the loading tasks is not significant.

To investigate the impact of utilising buffers in port A, we follow a sensitivity analysis approach by varying the size of buffers (i.e. the number of available places for cassettes next to a crane) from 1 to 10 and the number of IAVs from 3 to 25. Note that because IAVs need some additional time to pick up/drop off cassettes, we have to take this into account in the simulation with cassettes. It is estimated that the IAVs will need averagely 48 seconds to either pick up or drop off containers. Results of the simulation are presented in Tables 9 and 10.

Results in this experiment clearly show the advantages of using buffers. As mentioned earlier, Figure 7 shows that without cassettes it is not possible to increase net moves per hours to around 30 (no waiting time of quay cranes). Figure 9 shows that, however, with the use of cassettes a zero crane waiting time can be achieved with a much smaller fleet size (11 vehicles) if nine cassettes or more are used. There is also a wide range of combination of different fleet sizes and buffer sizes to achieve no waiting time for quay cranes as shown by the blue cells in Figure 9. The use of cassettes also allows achieving a reasonably high crane net moves per hour (almost more than 25 moves) with just nine or ten vehicles.

"place Figure 9 about here"

As can be seen in Figure 9 the impact of buffers on the productivity of quay cranes is significant. To investigate how much the total discharging time can be reduced by the utilisation of the buffers, we calculated this measure using Equations 4.1 and 4.2. The results are reported in Figure 10. It can be seen that with 11 IAVs and the size of buffer equals 10 the total discharging time is 3.98 hours, 1.95 hours smaller than the discharging time achieved by the same number of trucks (5.92 hours). In addition, if we use trucks we will not be able to achieve the small total discharging time achieved by IAVs (3.98 hours). Even if we increase the number of trucks to a large number of 25, the discharging time is still 4.63 hours, significantly larger than the value achieved by IAVs (Figure 8).

"place Figure 10 about here"

4.6. IAVs versus trucks: a total cost comparison

This section compares the values of IAVs and trucks based on the total capital and operational cost in a 15-year period.

4.6.1. Identifying the optimal number of vehicles

To compare the total cost of the two types of vehicles, we first need to identify the smallest number of vehicles (e.g. IAVs and trucks) that can meet the target set out by the port. Current port A suggests a target of 25 moves per hour if using two quay cranes, which is equivalent to 17 moves per hour if using three quay cranes. To identify such an optimal fleet size, we use simulation to identify the minimum number of vehicles that can meet the required target moves per hour for the largest transaction available in the port, in which 300 containers are discharged. The reason to only consider the largest transaction is that for smaller transactions naturally fewer vehicles are required to meet the target. By comparing Figures 7 and 9, it can be seen that with 6 IAVs and a buffer size of 5 or with 10 trucks this target of 17 moves per hour for three quay cranes can be achieved. Therefore, we consider six IAVs (with a buffer size of 5) and 10 trucks to be the optimal numbers of vehicles. Note that to identify the optimal number of vehicles we do not consider the loading cases given that in this container terminal the fleet size needed for loading is always less than the fleet size for discharging (as explained in the last paragraph of subsection 4.4 and also shown in Figure 8).

4.6.2. Cost model of port A

Identifying only the minimum fleet size for trucks and IAVs, however, does not answer the question of which type of vehicles is economically better and what would be the total cost for those vehicles. To answer this question, in this subsection, we develop a cost model (see details in the technical report in

(Kay McGinley, 2013)) to compare the total cost that port A needs to spend for its vehicles in 15 years when being used with the optimal fleet sizes of 6 IAVs against 10 trucks.

The cost model calculates the total cost that port A has to spend on each type of vehicles, taking into account the vehicles' capital and operational cost for a 15-year period. The purpose of this cost model is to estimate the total present values of each system (e.g. IAVs and trucks). The present value is a metric to show the total cash flows of an investment over a given period, discounted to the today's cash value (Bazargan et al., 2013). For this calculation we considered a discount rate of 5% and a 15-year period. We considered 10 years to be the lifetime of trucks and IAVs. The factors that were considered in this cost model are explained in this section.

The first factor in the cost model is the vehicles capital. The IAVs and trucks capital can have a significant impact on the total cost of port A. Note that by the time of submission, IAVs have not been manufactured commercially, therefore, the final price of IAVs has not been determined. However, the price of an IAV is estimated to be €500,000 plus €8,000 for a cassette and €2,000 for charger installation cost. The truck capital was considered €113,000 including €90,000 for a shunter and €23,000 for a trailer. It can be seen that an IAV is almost five time more expensive than a truck. To take into account failures of vehicles, in addition to the optimal fleet size, spare vehicles needs to be considered to cover failures. In reality port A uses 20% of the fleet as spare vehicles, which is equivalent to one IAV and two trucks, given their respective fleet size. Note that the cost model only considers the capital of the spare vehicles and the operational cost of the spare vehicles will not be included, given that the spare vehicles are supposed to cover only the failed vehicles and they will not carry out any other task.

Trucks consume diesel and IAVs use electricity, therefore the price of energy for the two types of vehicles can be different. To calculate the energy cost per year, the vehicle working hours per year is needed. We considered the same working hours for IAVs and trucks, given that the two types of vehicles are supposed to provide the same performance of port A. The total fuel cost of IAVs and trucks for one year are calculated as below:

Let:

h: total working hours per vehicle per year

d: diesel litre consumed per truck per hour

p_d: price per diesel litre

p_c: price per charge per IAV

w: IAV working hours per charge

E_{IAV}: total energy cost per IAV per year

E_{truck}: total energy cost per truck per year

$$E_{IAV} = p_c * (h/w) \tag{4.3}$$

$$E_{truck} = p_d * h * d \tag{4.4}$$

The next cost that we explain is the cost of periodic services. To calculate the service cost we considered n_s services per year for IAVs and trucks. The cost per service is shown by s_{IAV} for IAVs and for trucks by s_{truck}. Note that by the time of submission the exact maintenance and repair costs of IAVs were not available. Existing literature indicates that electric vehicles (like AGVs, IAVs etc) usually cost less to maintain and repair than diesel vehicles (like trucks) (Funk and Rabl, 1999; Nam and Ha, 2001; Lin et al., 2013). Despite that, in this paper we consider the worst-case scenario where the service cost of IAVs is the same as that of trucks. Using this information the total service cost of one year for an IAV, S_{IAV} and for a truck, S_{trucks} can be calculated as below:

$$S_{IAV} = s_{IAV} * n_s \tag{4.5}$$

$$S_{truck} = s_{truck} * n_s \tag{4.6}$$

Six IAVs need two operators and ten trucks need ten drivers. The cost for wages, insurance and annual leaves of an operator for IAVs and a driver for trucks were calculated based on the following parameters:

Let:

h: total working hours per year per vehicle

w_{IAV}: wage cost per hour per IAV operator

w_{truck}: wage cost per hour per truck driver

v_{IAV}: provision for holiday pay per year per IAV operator

v_{truck}: provision for holiday pay per year per truck driver

i_{IAV}: employers insurance per year per IAV operator

i_{truck}: employers insurance per year per truck driver

a_{IAV}: annual leave hours per year per IAV operator

a_{truck}: annual leave hours per year per truck driver

W_{IAV}: total wage cost per year per IAV operator

W_{truck}: total wage cost per year per truck driver

$$W_{IAV} = (w_{IAV} * h) + v_{IAV} + i_{IAV} + (w_{IAV} * a_{IAV}) \tag{4.7}$$

$$W_{truck} = (w_{truck} * h) + v_{truck} + i_{truck} + (w_{truck} * a_{truck}) \tag{4.8}$$

By calculating the above intermediate parameters (E, S and W), we can calculate the cash flows for the operational costs of IAVs and trucks. Equations 4.9 and 4.10 show how the cash flows for operational costs in year 0 (O_0) can be calculated.

Let:

d_{truck}: number of drivers for trucks

d_{IAV}: number of operators for IAVs

n_{truck}: optimal number of trucks

n_{IAV}: optimal number of IAVs

$$O_0^{truck} = (E_{truck} + S_{truck}) * n_{truck} + (W_{truck}) * d_{truck} \tag{4.9}$$

$$O_0^{IAV} = (E_{IAV} + S_{IAV}) * n_{IAV} + (W_{IAV}) * d_{IAV} \tag{4.10}$$

The cash flows for operational cost of the next 15 years are calculated using the cash flow for year 0 and the inflation rate i. This is shown by Equation 4.11.

$$O_t = O_0 * (i+1)^t,\ 1 \leq t \leq 15 \tag{4.11}$$

Equation 4.12 estimates the vehicle capital for the next 15 years in a similar way to that of the operational cost. Note that since the lifetime of the vehicles was considered 10 years, the capital cost were taken into account only in year 0 and 10 (Table 5).

$$C_t = \begin{cases} C_0 * (i+1)^t,\ if\ t = 10 \\ 0,\ otherwise \end{cases} \tag{4.12}$$

Equation 4.13 calculates R_t, the total cash flow of year t. To do so, it takes the summation of the operational cash flow (Q_t) and vehicle capital cost (C_t).

$$R_t = O_t + C_t,\ 0 \leq t \leq 15 \tag{4.13}$$

By calculation of R_t, $0 \leq t \leq 15$, we can calculate the present value of the cash flow of each year using Equation 4.15 where r is the risk adjusted discount rate.

$$P_t = R_t/(1+r)^t \tag{4.14}$$

Finally, Equation 4.15 calculates the total present value of the vehicle (TPV) by taking the summation of the present values of the cash flow of each year.

$$TPV = \sum_{t=0}^{15} P_t \tag{4.15}$$

Tables 3 and 4 show the values of the initial and intermediate parameters used in the cost model. The intermediate parameters were calculated by Equations 4.3-4.8. Table 5 shows the cash flows for the 15-year period that were calculated using Equations 4.9-4.13.

"place Table 3 about here"

"place Table 4 about here"

"place Table 5 about here"

Figure 11-a compares the present value of the cash flow in each year for IAVs and trucks. At year 0 the present value for IAVs is €3,787,374 and for trucks is €2,411,390. The present value in year 0 is the present value of cash flow, which is the summation of operational cost and vehicles capital, because in year 0 new fleet should be purchased. In year 1, the present cash flow value for IAVs is €211,163 which is significantly lower than €1,025,236 of cash flow

for trucks. In the next following years apart from year 10, similar trend as for year 1 can be observed. This shows that the operational cost of IAVs is much lower than that of trucks. This is mainly because of the higher price of energy for trucks compared with that of IAVs (Table 4) and also the optimal number of trucks is higher than that of IAVs (Table 3). The reason to have a significant increase in the present cash flow values of trucks and IAVs in year 10 is that new vehicles should be replaced with the current fleet (the lifetime of vehicles was considered 10 years). Next, we compare the total present values for IAVs and trucks. As in Figure 11-b, the total present cash flow values for IAVs is €9,306,017 and for trucks is €15,395,869. As one can see, the total present value for the IAV system is significantly lower than trucks despite the fact that IAVs is much more expensive than trucks. Thanks to the IAV's unique feature of utilising the buffers of containers, fewer IAVs are needed compared with trucks. Being electric, IAVs also lead to less energy cost than trucks.

"place Figure 11 about here"

5. Advanced vehicle dispatching/scheduling and container placement strategies

In this section, we study the performance of port A with advanced vehicle dispatching/scheduling and container placement strategies from literature.

5.1. Advanced vehicle dispatching strategy

Recall from subsection 3.5, the vehicle dispatching strategy used in port A is not very sophisticated compared with existing advanced on-line dispatching/scheduling in the literature. It is also quite basic in comparison to practical scheduling algorithms currently being used in large container terminals such as

Rotterdam and Hamburg. It does not consider the release time of upcoming containers effectively nor give any priority to the delayed jobs to reduce the possible waiting time of quay cranes. To address these limitations and also to investigate the impact of an advanced on-line dispatching/scheduling algorithm on the performance of port A, we apply a dynamic vehicle scheduler (DVS) from literature (Angeloudis and Bell, 2010)[6] to the case study in port A.

In Angeloudis and Bell (2010), an integer programming (IP) formulation was proposed to dynamically update the schedule of vehicles based on: 1) release time of upcoming jobs (i.e. containers); 2) information regarding delayed jobs; and 3) earliest time that vehicles can be available to carry out jobs. This DVS also monitors the environment periodically and if any unpredicted change (e.g. any waiting of cranes and vehicle, breakdown of equipment etc) happens to the environment, DVS will then adapt the schedule of vehicles to the changes. The advantage of this DVS algorithm is its low computational cost: it only schedules vehicles in a very small future horizon, knowing that any schedule beyond this horizon would likely be unusable due to environmental changes.

Thanks to this low computational cost, the model can be solved quickly, making it feasible to integrate the scheduling model into a simulation. Readers are referred to Angeloudis and Bell (2010) for more detailed information about this on-line scheduler.

We coded this IP model in C++ using the CPLEX Concert Technology and connected it to the simulation. The developed simulation model triggers DVS frequently and pass the required input parameters to DVS. DVS will then provide the optimal schedules for vehicles using the CPLEX engine based on the provided inputs. Results of incorporating DVS to the simulation will be

[6]For a recent literature review on vehicle dispatching strategy in container terminals the reader is referred to Carlo et al. (2014b)

discussed later in this section.

5.2. Advanced container placement strategy

In this section, we also investigate the impact of using an advanced container placement strategy on the performance of port A. As discussed in subsection 3.4, the container placement strategy (called Levelling) currently being used in port A is not very efficient. This is due to that Levelling does not consider the dwell time of containers (i.e. due time of containers for unstacking). For instance, with Levelling it is possible that a container that will leave later will be placed on top of a container that will leave sooner. It means that a crane would need to carry out some unproductive moves to reach the container that will leave sooner. To address this limitation, we implemented a more advanced container placement strategy adopted from literature (Hamdi et al., 2012)[7]. This strategy is an improved version of the strategy proposed in Duinkerken et al. (2001). In this paper, we refer to this strategy as Dwell Time-based Strategy (DTS).

DTS (Hamdi et al., 2012) defined a number of categories for containers based on their dwell times. The containers with higher categories should be placed under containers with lower categories, given that their dwell time is later. To identify the best position for a container with respect to reducing the number of possible re-locations, the method uses a number of mathematical equations and logical rules. For details of the mathematical models of the method, readers are referred to Hamdi et al. (2012).

5.3. Experimental results

To show the impact of the aforementioned strategies on the performance of port A, we develop a simulation model of the port, using the two aforementioned online scheduling (DVS) and container placing (DTS) strategies, with an

[7]A recent literature review on this topic can be found in Carlo et al. (2014a)

optimal fleet size of six IAVs (as identified in Subsect. 4.6.1, IAVs are found more beneficial to port A than trucks). We then use this simulation to compare the impact of DVS, DTS on port performance in comparison to the strategies currently used in ports (WDS and Levelling). We also investigate different combinations of DVS, DTS, WDS and Levelling to see which one will best benefit a small-medium port like port A.

For this experiment, we used the same settings for the simulation as explained in Section 3. Furthermore, similar to Section 4, we consider the followings performance measures: 1) the quay crane net moves per hour; and 2) total discharging time. Figures 12 and 13 show the improvement brought by DVS and DTS to the performance of the port.

"place Figure 12 about here"

"place Figure 13 about here"

As shown in Figure 12, in comparison to WDS, DVS can improve the performance of the port in all simulation scenarios. Another interesting observation in Figure 12 is that when DVS is used the three quay cranes have almost equal net moves per hour, whereas when WDS is used quay crane 2 has significantly higher net moves per hour than the two other quay cranes. This shows that DVS can provides a better balance between quay crane compared with WDS.

Regarding the impact of advanced container placement strategies, it can be seen that the impact of DTS on the performance of port A is not very significant, even though it provides slightly better productivity. One reason for such a behaviour is that the port is a small-size container terminal and it deals with a limited number of containers and hence the Levelling strategy seems to be efficient enough for the current workload of this port.

6. Conclusion

The simulation results reveal three findings: first, when not using the cassettes, IAVs are still shown to have similar efficacy to regular trucks, even though the IAVs were chosen to operate in a much slower speed than the trucks. Due to their ability to move in all directions without having to turn, IAVs can save the travel time compared with trucks, leading to better efficiency. Of course, the efficacy could be improved considerably if IAVs are allowed to travel with a higher speed. Second, combining IAVs with cassettes significantly improves port performance in terms of the number of crane moves per hour and total loading/discharging time. By comparing the total present values of the two vehicle systems, it can be concluded that the total present value for IAVs is much lower than that of trucks even though the IAVs capital is much higher than that of trucks. Finally, for a small-medium container terminal like port A, using an advanced online scheduling strategy like DVS can significantly improve performance. This is the first research that uses simulation to study the impact of using IAVs in container terminals. With the potential improvements shown to be significant, this study is expected to have practical impacts and the research results are being considered by the studied port.

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Abstract

In this paper, we study the impact of using a new intelligent vehicle technology on the performance and total cost of a European port, in comparison with existing vehicle systems like trucks. Intelligent autonomous vehicles (IAVs) are a new type of automated guided vehicles (AGVs) with better maneuverability and a special ability to pick up/drop off containers by themselves. To identify the most economical fleet size for each type of vehicle to satisfy the port's performance target, and also to compare their impact on the performance/cost of container terminals, we developed a discrete-event simulation model to simulate all port activities in micro-level (low-level) details. We also developed a cost model to investigate the present values of using two types of vehicle, given the identified fleet size. Results of using the different types of vehicles are then compared based on the given performance measures such as the quay crane net moves per hour and average total discharging/loading time at berth. Besides successfully identifying the optimal fleet size for each type of vehicle, simulation results reveal two findings: first, even when not utilising their ability to pick up/drop off containers, the IAVs still have similar efficacy to regular trucks thanks to their better maneuverability. Second, enabling IAVs' ability to pick up/drop off containers significantly improves the port performance. Given the best configuration and fleet size as identified by the simulation, we use the developed cost model to estimate the total cost needed for each type of vehicle to meet the performance target. Finally, we study the performance of the case study port with advanced real-time vehicle dispatching/scheduling and container placement strategies. This study reveals that the case study port can greatly benefit from upgrading its current vehicle dispatching/scheduling strategy to a more advanced one.

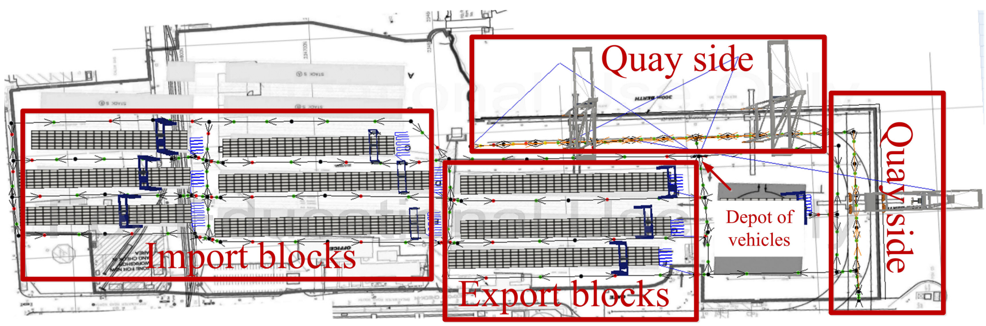


Figure 1: This figure shows the position of import/export blocks in the stack-side area and also the berths at the quay-side area.

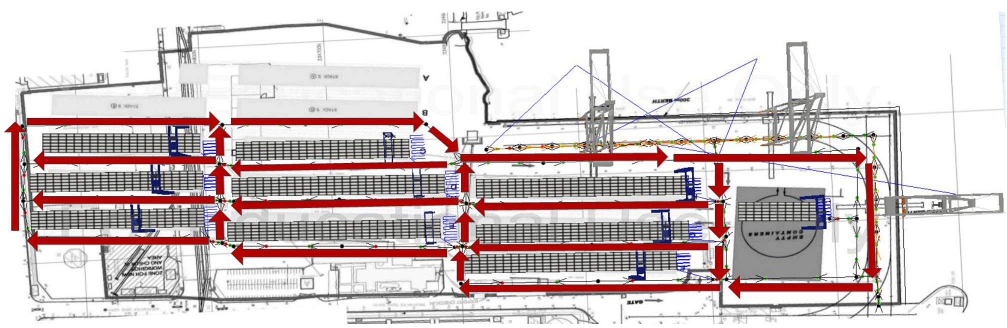


Figure 2: This figure shows the travel routes of trucks in port A.

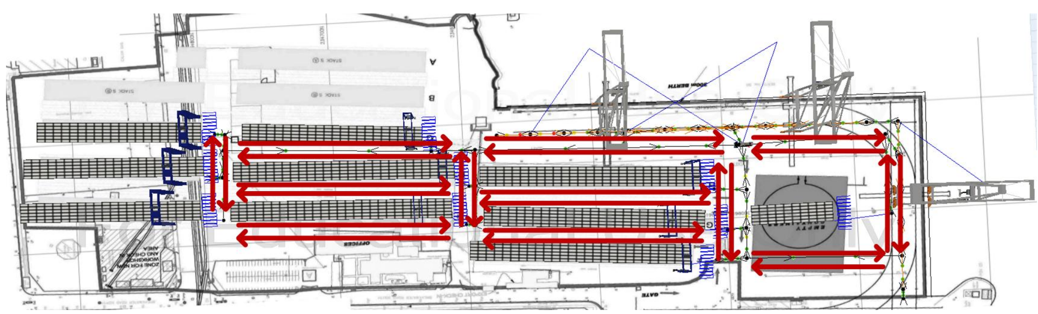


Figure 3: The proposed travel routes of IAVs. In these routes, IAVs do not need to go to the end of the roads to turn around or follow a loop like trucks. Instead, they can move forward, backward, or sideways using the shortest available path.

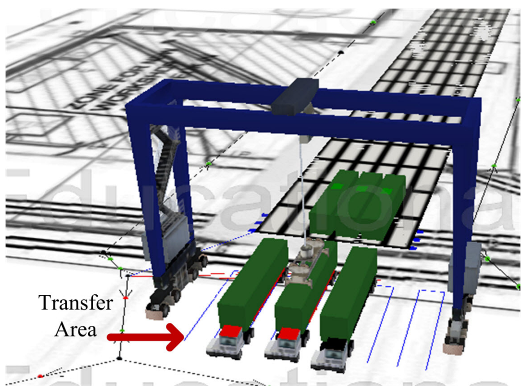
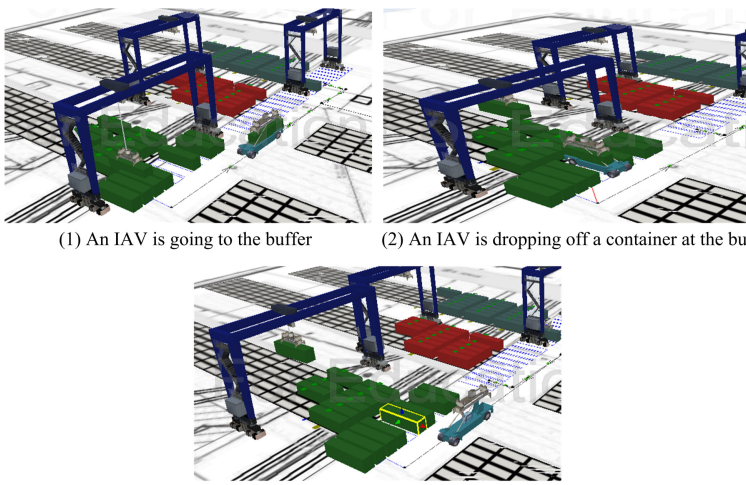


Figure 4: This figure shows how the transfer area can be used by trucks.

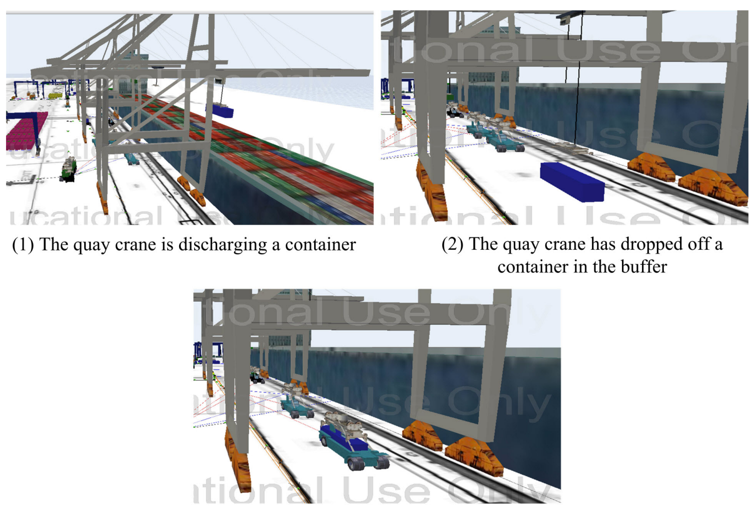


(1) An IAV is going to the buffer

(2) An IAV is dropping off a container at the buffer

(3) An IAV is leaving the buffer after dropping off a container

Figure 5: Transition of containers between IAVs and stacking cranes in the stack-side area.

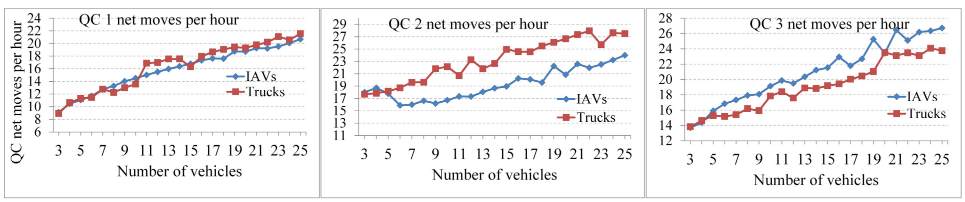


(1) The quay crane is discharging a container

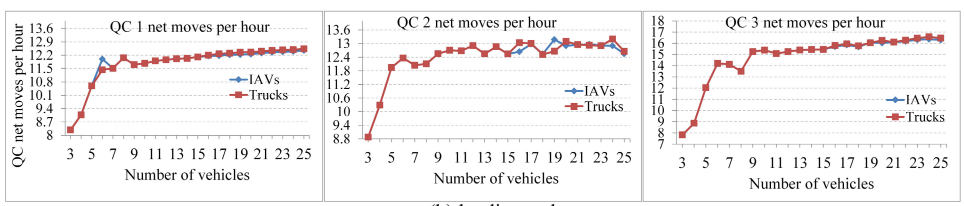
(2) The quay crane has dropped off a container in the buffer

(3) An IAV picks up a container from the buffer

Figure 6: Transition of containers between IAVs and quay cranes in the quay-side area.

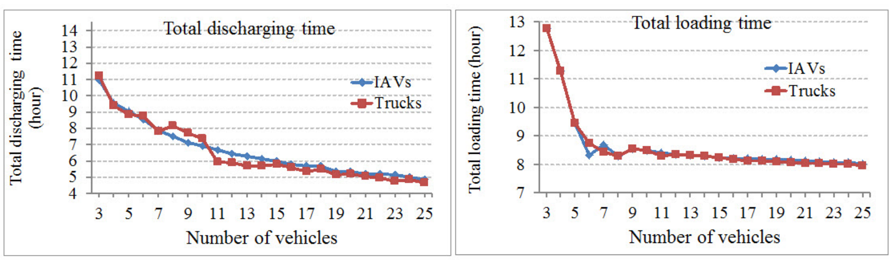


(a) discharging tasks



(b) loading tasks

Figure 7: Trucks vs IAVs *without* cassettes. Plot (a) shows the quay crane net moves per hour for the discharging tasks. Plot (b) shows the quay crane net moves per hour for the loading tasks.



(a) discharging tasks (b) loading tasks

Figure 8: Comparing the total discharging/loading times at berth using IAVs (without cassettes) and trucks. As can be seen the total discharging/loading time at berth for IAVs and trucks are similar especially when the number of vehicles is greater than five.

Size of buffer	Number of IAVs																						
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Quay crane 1 net moves per hour																						
10	1.2	6.5	9.6	12.1	14.4	16.4	18.8	21.9	25.1	27.5	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
9	1.0	6.4	9.4	11.8	14.1	15.7	18.1	21.3	23.5	26.0	29.6	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
8	0.9	6.3	9.3	11.8	13.5	15.4	17.6	19.7	22.0	23.9	26.9	29.2	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
7	0.7	6.2	9.2	11.5	13.2	14.6	16.9	18.7	20.8	22.2	24.8	26.4	28.2	29.4	29.9	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
6	0.8	6.2	9.1	11.3	12.9	14.0	16.0	17.6	19.4	20.5	21.9	24.1	25.8	27.2	28.3	29.2	29.6	29.8	29.9	30.0	30.0	30.0	30.0
5	0.7	6.1	9.0	10.9	12.4	13.4	15.0	16.9	18.7	19.7	20.3	21.8	23.0	23.9	25.0	26.3	26.9	27.9	28.5	29.0	29.4	29.8	30.0
4	0.5	6.0	8.8	10.8	11.9	13.1	13.9	15.6	17.3	18.3	18.9	20.1	20.8	21.9	22.9	23.7	24.0	24.9	25.2	26.2	26.9	27.4	28.2
3	0.4	6.0	8.6	10.2	11.6	12.6	13.4	14.3	16.2	17.2	18.4	18.5	19.6	20.2	20.8	21.2	22.1	22.2	22.7	23.2	23.8	24.2	24.8
2	0.3	5.9	8.6	10.1	10.8	11.8	12.7	13.4	14.7	15.7	16.5	17.4	17.9	18.3	18.9	19.6	19.9	20.1	20.9	21.1	21.5	22.2	23.2
1	0.3	5.9	8.4	9.8	10.5	11.3	12.5	13.2	14.3	14.5	15.1	15.7	16.6	17.4	18.2	18.5	18.7	19.1	19.6	19.9	20.5	21.0	21.5
	Quay crane 2 net moves per hour																						
10	11.0	12.4	12.7	17.0	20.5	24.3	26.9	28.4	28.8	29.7	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9
9	10.7	12.4	12.1	16.9	20.1	23.8	26.6	28.0	28.3	29.4	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9
8	10.7	12.1	12.2	16.5	20.0	23.2	26.0	27.8	27.6	28.5	29.4	29.8	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9
7	10.5	11.9	12.1	16.3	19.6	22.7	25.2	26.9	27.0	27.5	28.6	29.3	29.8	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9	29.9
6	10.3	12.0	11.8	16.0	19.1	22.4	24.2	26.0	26.5	26.3	27.0	28.1	29.1	29.5	29.6	29.8	29.9	29.9	29.9	29.9	29.9	29.9	29.9
5	10.3	11.4	11.9	15.8	19.0	22.2	23.4	24.9	25.7	25.7	26.1	26.7	27.3	28.1	28.8	28.9	29.4	29.5	29.7	29.8	29.8	29.9	29.9
4	10.1	11.6	11.1	15.8	18.8	21.0	22.4	23.6	24.3	25.2	25.8	25.6	26.2	26.3	27.0	27.4	28.0	28.3	28.6	28.9	29.2	29.5	29.6
3	10.0	11.3	11.4	15.6	18.4	20.3	21.7	22.6	23.3	23.7	24.4	25.7	25.5	25.3	25.8	26.2	26.4	26.6	27.2	27.4	27.9	28.1	28.4
2	9.9	11.3	11.4	15.3	17.9	19.5	20.3	21.1	21.9	22.5	23.1	23.9	24.1	25.1	25.0	25.0	25.1	26.0	25.9	26.2	26.9	26.8	27.0
1	9.9	11.5	11.3	15.3	17.3	18.4	19.4	20.0	20.6	21.4	22.1	22.9	23.3	23.5	23.7	23.9	25.2	25.3	25.4	25.6	26.2	26.2	26.4
	Quay crane 3 net moves per hour																						
10	5.1	9.6	9.9	14.3	17.8	20.6	23.3	25.9	27.4	28.9	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
9	5.1	9.5	9.9	14.5	17.5	19.9	23.3	25.2	26.1	28.2	29.5	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
8	5.1	9.5	9.8	14.6	17.2	19.4	22.7	24.3	24.9	26.5	28.4	29.2	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
7	4.9	9.4	9.6	13.9	16.8	18.7	21.5	23.4	23.9	24.9	26.8	28.1	29.2	29.6	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
6	4.9	9.3	9.4	13.9	16.4	18.3	20.7	22.3	23.4	24.0	25.0	26.3	27.6	28.3	29.2	29.5	29.6	29.7	29.7	29.7	29.7	29.7	29.7
5	4.9	9.3	9.2	13.4	15.8	17.3	19.8	21.3	22.5	22.6	23.6	24.5	25.2	26.1	26.9	27.9	28.4	28.8	29.1	29.5	29.6	29.7	29.7
4	4.6	9.2	9.3	13.6	15.1	16.8	18.1	20.0	20.8	22.0	22.7	23.3	23.9	24.5	24.9	25.5	25.8	26.7	27.2	27.9	28.1	28.8	29.0
3	4.8	9.1	8.9	12.9	14.9	16.2	17.4	18.3	19.7	20.0	21.3	22.4	22.6	23.1	23.4	23.9	24.3	24.7	25.0	25.4	26.1	26.4	26.8
2	4.7	9.0	8.6	13.1	14.0	15.3	16.3	17.1	17.8	18.4	19.8	20.3	20.5	21.6	21.9	22.0	22.3	23.1	23.1	23.6	24.2	24.8	25.4
1	4.6	9.2	8.6	12.8	13.5	14.7	15.9	16.1	17.0	17.3	18.2	18.6	19.4	20.1	20.6	21.0	21.6	21.7	22.5	22.7	23.5	23.8	24.2

Figure 9: Quay crane net moves per hour by varying the number of vehicles from 3 to 25 and size of the buffer from 1 to 10.

Size of buffer	Number of IAVs																						
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Total discharging time (hour)																						
10	83.65	15.42	10.46	8.29	6.94	6.08	5.33	4.57	3.98	3.63	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37
9	95.90	15.62	10.65	8.50	7.09	6.38	5.52	4.70	4.25	3.84	3.39	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37
8	110.11	15.86	10.74	8.45	7.40	6.49	5.68	5.08	4.55	4.19	3.72	3.43	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37
7	133.48	16.03	10.84	8.73	7.57	6.87	5.91	5.35	4.81	4.50	4.03	3.79	3.54	3.40	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37
6	126.11	16.11	11.01	8.88	7.73	7.12	6.25	5.67	5.16	4.87	4.56	4.14	3.87	3.67	3.53	3.43	3.38	3.37	3.37	3.37	3.37	3.37	3.37
5	152.75	16.37	11.16	9.19	8.08	7.47	6.65	5.93	5.35	5.09	4.94	4.58	4.35	4.18	3.99	3.81	3.72	3.59	3.51	3.44	3.40	3.37	3.37
4	217.07	16.54	11.42	9.30	8.40	7.62	7.20	6.43	5.79	5.46	5.28	4.97	4.81	4.57	4.37	4.23	4.17	4.02	3.97	3.82	3.72	3.64	3.55
3	256.09	16.78	11.57	9.79	8.63	7.96	7.47	7.02	6.18	5.80	5.44	5.40	5.10	4.96	4.82	4.72	4.53	4.51	4.40	4.31	4.21	4.13	4.03
2	297.47	16.98	11.66	9.86	9.23	8.49	7.88	7.46	6.80	6.38	6.06	5.73	5.59	5.46	5.30	5.11	5.04	4.98	4.79	4.73	4.65	4.50	4.30
1	292.64	16.98	11.96	10.24	9.52	8.83	7.97	7.58	6.99	6.91	6.60	6.38	6.01	5.74	5.50	5.39	5.33	5.23	5.11	5.03	4.88	4.76	4.66

Figure 10: The total discharging time using IAVs by utilising the buffers.

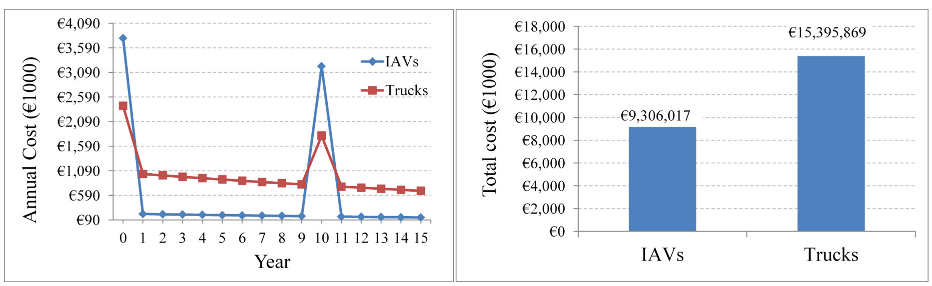


Figure 11: Plot (a) compares the present cash flow values of cost of trucks and IAVs in each year. Plot (b) compares the total present value of trucks against that of IAVs over 15 years. As can be seen the total present value for IAVs is much lower than that of trucks.

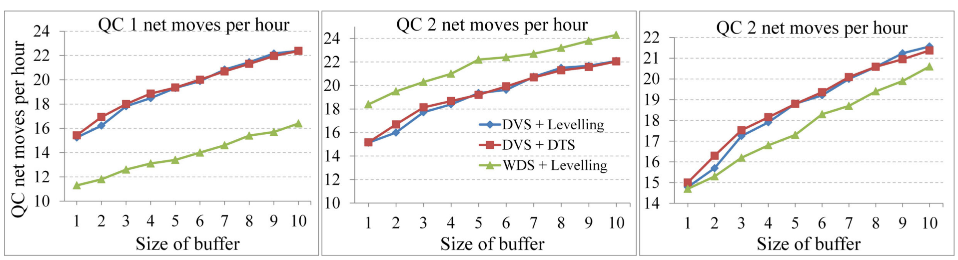


Figure 12: Comparison between different combinations of scheduling and container placement strategies.

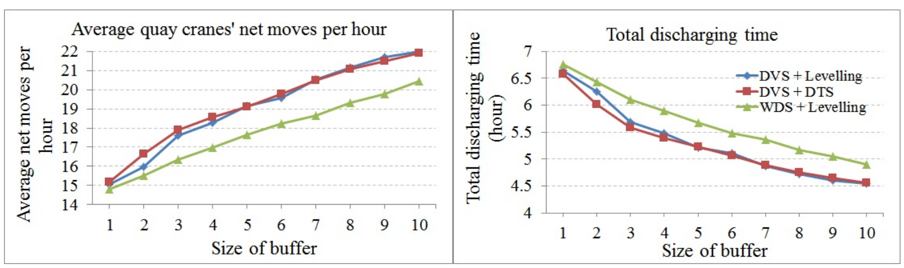


Figure 13: Average QCs' net moves per hour and total discharging time with DVS and DTS.

Table 1: Vehicle speeds in the simulation models.

	Truck	IAV
empty speed (m/s)	13.41	4
loaded speed (m/s)	11.18	2
acceleration (m/s^2)	1	0.5

Table 2: Statistical comparison of results of trucks vs IAVs without the cassettes for the discharging case.

Fleet size	Type of vehicle that the minimum discharging time is achieved by	Are results with this type of vehicle significantly better than those of the other type of vehicle?	P-value
3	IAV	Yes	1.59e-11
4	Truck	Yes	2.39e-05
5	Truck	Yes	2.73e-02
6	IAV	Yes	9.75e-08
7	Truck	No	2.97e-01
8	IAV	Yes	1.44e-11
9	IAV	Yes	1.44e-11
10	IAV	Yes	1.44e-11
11	IAV	Yes	3.72e-09
12	Truck	Yes	1.44e-11
13	Truck	Yes	1.59e-11
14	Truck	Yes	1.59e-11
15	IAV	Yes	3.40e-08
16	Truck	Yes	1.44e-11
17	Truck	Yes	1.44e-11
18	Truck	Yes	1.59e-11
19	Truck	No	3.88e-11
20	Truck	Yes	1.59e-11
21	Truck	Yes	1.75e-11
22	Truck	Yes	2.14e-11
23	Truck	Yes	1.94e-11
24	IAV	Yes	1.03e-04
25	Truck	Yes	1.23e-04

Table 3: Parameters used in the cost model and their values, as provided by the port.

Parameter description	Symbol	Unit	Value
Total working hours per year	h	h/year	3,000
Diesel litre consumed per hour per truck	d	l/h	8
Price per diesel litre	p_d	€/l	0.9
Price per charge per IAV	p_c	€/c	3.89
IAV working hours per charge	w	h/c	4
Wage cost per hour per IAV operator	w_{IAV}	€/h	19
Wage cost per hour per truck driver	w_{truck}	€/h	19
Provision for holiday pay per year per IAV operator	v_{IAV}	€/year	6,080
Provision for holiday pay per year per truck driver	v_{truck}	€/year	6,080
Employers insurance per year per IAV operator	i_{IAV}	€/year	6,779
Employers insurance per year per truck driver	i_{truck}	€/year	6,779
Annual leave hours per year per IAV operator	a_{IAV}	h/year	320
Annual leave hours per year per truck driver	a_{truck}	h/year	320
Number of services per year per vehicle	n_s	1/year	10
Cost of a service per IAV	s_{IAV}	€	800
Cost of a service per truck	s_{truck}	€	800
Number of operators for the IAV system	d_{IAV}	person	2
Number of drivers for the truck system	d_{truck}	person	10
Optimal number of IAVs	n_{IAV}	vehicle	6
Number of spare IAVs	$n_{IAV-spare}$	vehicle	1
Optimal number of trucks	n_{truck}	vehicle	10
Number of spare trucks	$n_{truck-spare}$	vehicle	2
Risk adjusted discount rate	r	-	0.05
Inflation rate	i	-	0.02
IAV capital (IAV + cassette + charger)	C_0^{IAV}	€	510,000
Truck capital (shunter + trailer)	C_0^{truck}	€	113,000

Table 4: Intermediate parameters calculated using the parameters in Table 3 and Equations 4.3-4.8 for year 0.

Parameter description (for year 0)	Symbol	Unit	Value
Total energy cost per IAV	E_{IAV}	€	2,916
Total energy cost per truck	E_{truck}	€	21,600
Total wage cost per IAV operator	W_{IAV}	€	75,939
Total wage cost per truck driver	W_{truck}	€	75,939
Total service cost per IAV	S_{IAV}	€	8,000
Total service cost per truck	S_{truck}	€	8,000

Table 5: Cash flows for IAVs and trucks for the 15-year period. The unit for Q_t, C_t and R_t is Euro (€). These cash flows were calculated using Equations 4.9-4.13. Note that since the lifetime of trucks and IAVs is 10 years, at year 0 and year 10 a new fleet should be purchased and thus C_t in all years apart from years 0 and 10 have the value of 0.

Year	Trucks			IAVs		
	Q_t^*	C_t	R_t	Q_t	C_t	R_t
0	2,298,390	113,000	2,411,390	3,277,374	510,000	3,787,374
1	1,076,498	0	1,076,498	221,721	0	221,721
2	1,098,028	0	1,098,028	226,156	0	226,156
3	1,119,988	0	1,119,988	230,679	0	230,679
4	1,142,388	0	1,142,388	235,293	0	235,293
5	1,165,236	0	1,165,236	239,998	0	239,998
6	1,188,541	0	1,188,541	244,798	0	244,798
7	1,212,311	0	1,212,311	249,694	0	249,694
8	1,236,558	0	1,236,558	254,688	0	254,688
9	1,261,289	0	1,261,289	259,782	0	259,782
10	2,801,725	137,746	2,939,471	4,616,788	621,687	5,238,475
11	1,312,245	0	1,312,245	270,277	0	270,277
12	1,338,490	0	1,338,490	275,683	0	275,683
13	1,365,260	0	1,365,260	281,196	0	281,196
14	1,392,565	0	1,392,565	286,820	0	286,820
15	1,420,416	0	1,420,416	292,557	0	292,557

*Q_t: operational cost at year t

C_t: vehicles capital at year t

R_t: total cash flow (i.e. $Q_t + C_t$) at year t

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Keywords

Discrete-event simulation, fleet sizing, intelligent autonomous vehicles, automated guided vehicles, container terminals, cost-benefit analysis