Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

EVALUATION OF INTER TERMINAL TRANSPORT CONFIGURATIONS AT ROTTERDAM MAASVLAKTE USING DISCRETE EVENT SIMULATION

Herbert J.L. Schroër
Francesco Corman
Mark B. Duinkerken
Rudy R. Negenborn
Gabriel Lodewijks

Delft University of Technology
Mekelweg 2
2628 CD Delft, THE NETHERLANDS

ABSTRACT

In this paper, various Inter Terminal Transport (ITT) systems for the Port of Rotterdam are evaluated. The Port Authority is investigating possible solutions for the transport of containers between terminals at the existing so-called Maasvlakte 1 and new Maasvlakte 2 areas within the port. A discrete event simulation model is presented that incorporates traffic modeling, which means that delays occurring due to traffic will have an impact on the system's performance. The model is applied to four different ITT vehicle configurations, including Automated Guided Vehicles (AGVs), Automated Lifting Vehicles (ALVs), Multi Trailer Systems (MTSs) and a combination of barges and trucks. Furthermore, three realistic demand scenarios for the year 2030 are used for the analysis.

1 INTRODUCTION

Over the past decades there has been an increasing demand in global containerized transport. Because of this demand the Port of Rotterdam was forced to expand its Maasvlakte 1 with the new Maasvlakte 2. It is expected that in 2040 the combined Maasvlakte 1 and 2 will handle at least 30 million twenty-foot equivalent unit (TEU) containers, which is almost four times as much as the entire Port of Rotterdam is handling now (Diekman and Koeman 2010). With this rise in container transport and new container terminals being built at Maasvlakte 2, there will also be a rise in Inter Terminal Transport (ITT). ITT is the transport of containers between terminals in a port.

1.1 Project Background

The ITT system for the Maasvlakte is being analyzed within the project "Inter-terminal transport on Maasvlakte 1 and 2 in 2030 - Towards a multidisciplinary and innovative approach on future inter-terminal transport options". It is a joint project between Delft University of Technology, Erasmus University Rotterdam and the Port of Rotterdam Authority in collaboration with Hamburg University. The goal of the project is to develop innovative, non-conventional concepts for ITT for the port of Rotterdam. Within this project, a common dataset for the study of the Maasvlakte terminals is developed by Duinkerken and Negenborn (Duinkerken and Negenborn 2014) and the expected transport demand scenarios for 2030 have been defined by Gerritse (Gerritse 2014). An integer programming model has been proposed by Nieuwkoop (Nieuwkoop, Corman, Negenborn, Duinkerken, van Schuylenburg, and Lodewijks 2014) to find rough estimations of the optimal transport configurations for the given transport demand scenarios.

1.2 Research Goal

The question that remains is “Which of the defined ITT vehicle configurations is the best configuration seen from an operational perspective?” Goal of this research is to find out how a number of given configurations perform. What is ’best’ is hereby defined using a number of performance criteria, as detailed in Section 3.4. For that, a discrete event simulation model for an ITT system at Maasvlakte 1 and 2 has been developed. The model makes it possible to evaluate all ITT vehicle configurations in combination with all the demand scenario’s for 2030.

1.3 Outline

The remainder of this paper is structured as follows. After a literature review in Section 2, the problem is described in more detail in Section 3. Then, the simulation model and its components are presented in Section 4. After verification and validation, an experimental plan is executed from which some results are given in Section 5. Finally the conclusions are drawn and recommendations for further work are given in Section 6.

2 LITERATURE

We briefly review here the approaches for studying systems such as the ITT system. When looking at discrete simulation applications in ports, most research centers around container terminals. We refer for a general background to the literature review in Vis and de Koster (Vis and de Koster 2003). From a modeling point of view, an ITT system shares many similarities with other container handling processes. A distinction can be made between exact and simulation based approaches.

Exact approaches for scheduling container movements have the drawback of a sharp increase in computation time when problem sizes achieves realistic scales. Le et al. (Le, Yassine, and Moussi 2012) focus on the scheduling of automated lifting vehicles. They look for an optimal solution by combining a DC (Difference of Convex functions) algorithm with a branch and bound method. Peterkofsky et al. (Peterkofsky and Daganzo 1990) develop an exhaustive search method to solve the static quay crane scheduling problem in a maritime container terminal, for the objective of minimizing delay costs. Exhaustive search is also used by Ng et al. (Ng and Mak 2005) to define an optimal schedule for yard cranes to perform a given set of loading/unloading jobs with different ready times. The objective is to minimize the sum of job waiting times. Tierney et al. (Tierney, Voss, and Stahlbock 2013) present a novel integer programming model for analyzing ITT in new and expanding seaports. The model can operate with 4 different vehicle types: AGVs, ALVs, MTSs and barges. The model takes congestion into account by giving intersection arcs a maximum capacity. The objective is to minimize the amount of containers delivered late. A future research direction envisaged by that paper is to analyze the outputs by means of a discrete event simulation tool, so to consider a more comprehensive set of realistic performance indicators. A similar approach was further used to study the interplay of operations costs and vehicle costs in supporting the design of an ITT system (Nieuwkoop, Corman, Negenborn, Duinkerken, van Schuylenburg, and Lodewijks 2014). Other ways of determining container operations include heuristics and simulation approaches. Kim et al. (Kim and Park 2004) report on a heuristic dispatching rule with look-ahead that is able to achieve an average deviation of 10% from the optimal solution, with only 0.01% of the computational time. Bish et al. (Bish, Chen, Leong, Nelson, Wing, Ng, and Simchi-Levi 2005) use a greedy algorithm for the dispatching of AGVs in a mega container terminal, achieving an optimality gap from optimal solution of 1.55% on average.

Simulation based approaches are widely used in container operations. Gambardella et al. (Gambardella, Rizzoli, and Zaffalon 1998) present a container terminal simulation model which is used as a decision support tool in the management of a real world intermodal terminal. The model is focused on resource allocation, and uses Operations Research techniques in order to generate resource allocation plans. Henesey et al. (Henesey, Davidsson, and Persson 2009) use multi-agent system techniques to study the assignment process of containers flows to AGVs, for evaluation of different AGV configurations.

The research on ITT starts with a large research project commissioned by Incomaas (Incomaas 1994, Duinkerken, Dekker, Kurstjens, Ottjes, and Dellaert 2006), focused at the Maasvlakte 1 area in the Port of Rotterdam. A detailed discrete simulation model was built, simulating operations at container level. Each terminal consists of a number of handling centers, where a number of equipment transfer containers from and onto the vehicles. Based on assumed container flows (incoming and outgoing ships, trains and barges), decisions on loading/unloading vehicles and their movements are taken, to minimize lateness (non-performance). The evaluation includes also vehicle occupation rates, equipment occupation rates and the number of vehicles waiting at the terminals. As part of the FAMAS.MV2 project (van Schuylenburg, Stijlen, Stubenitsky, Weustenenk, and Pons 2002), Ottjes et al. (Ottjes, Veeke, Duinkerken, Rijsenbrij, and Lodewijks 2006) used a new simulation model to evaluate conceptual multi-terminal designs for the second Maasvlakte (MV2), including ITT, in coherence with the existing terminals on the first Maasvlakte (MV1). The research assumed a transport demand scenario for 2025 with a fully developed MV2, that later turned out not be constructed. The research focus is mostly on stack content and traffic density and not so much on the performance of the system. A similar design problem has been tackled by Diekman and Koeman (Diekman and Koeman 2010), who investigated whether the capacity of the existing infrastructure on the Maasvlakte is enough for the expected ITT transport. They predict that until 2020 the ITT can be performed using 3 TEU trucks on the public road, but after 2020 a new and more sophisticated ITT system has to be developed. One proposal is a closed transportation route on which various types of vehicles can perform ITT without interaction with other traffic.

All those simulation approaches considered traffic density only to analyze traffic flows, while congestion was not integrated in decisions and travel time of vehicles during the simulation itself. We analyze this issue in more detail.

Van Burgsteden et al. (van Burgsteden, Joustra, Bouwman, and Hullegie 2000) distinguish between lateral interactions (i.e. crossings) and longitudinal interactions (i.e. a vehicle slowing down another one). Delays from lateral interactions are the majority, and obey the following characteristics: intersections are crossed in a passing order (passive: queuing, or active: traffic lights); vehicles in queue cannot overtake each other. Intersections can be modelled as multiple-servers queues, priority rules for passing orders (or time slices for traffic lights) and a process time dependent on the time the vehicle needs to clear the area. Egbelu et al. (Egbelu and Tanchoco 1986) present a traffic flow model for AGV based systems, based on a time-discretized setting. Intersections are modeled by a buffer with infinite capacity for each incoming direction, where vehicles can wait. A conflict resolution algorithm determines which vehicle is allowed to cross the intersection first. Liu et al. (Liu, Jula, Vukadinovic, and Ioannou 2004) use a control logic to guarantee a smooth traffic flow of AGVs within a yard. Low Speed Zones defined by the speed of the slowest AGV are used to avoid longitudinal conflicts. A "Modified First Come First Pass" concept is used instead for lateral conflicts, determining which vehicle can go first, blocking the intersection for all other traffic. To model this blocking behavior, Evers et al. (Evers and Koppers 1996) introduce the concept of semaphore (as defined in computer science) as an abstraction of a traffic light which controls the admissions of approaching vehicles individually. The semaphore concept was further used by Duinkerken et al. (Duinkerken, Evers, and Ottjes 1999) to develop a control system to coordinate AGV traffic flows.

A similar issue with congestion at intersections is faced by modeling them for vehicular traffic. The simplest intersection models are so called merge and diverge, that are described for instance by Daganzo (Daganzo 1995). The goal is to maximize the total flow outgoing from the intersection. If the intersection is demand-constrained, queue arises at one of the links directed at the intersection; traffic models try to replicate behavior of individualistic drivers, i.e. a link on which queue is formed has different "strength" against the other in the competition for passing over the intersection. Naive simple models result in unfair behavior, i.e., the vehicles in queue do not get any extra priority over other links that are not exhibiting queue. Many further developments have been therefore presented to limit this phenomena, by for instance use priority proportional to queue length, disregard the problem to maximize flow, neglect continuity over infinitesimal time steps when approaching queue formation. A comparative discussion of intersection modelling with macroscopic detail is given by Tampère (Tampère, Corthout, Cattrysse, and Immers 2011), along with general rules to comply for modelling traffic at intersections. In our setup instead, we assume AGV and other vehicles to operate according to orders and full compliance. This simplifies the modelling of the behavior of the interesections, and does note result in the principle of flow maximixation. Practical simulation models for traffic evaluation or generic are in general based on extensions of the principles here described. This includes also commercial simulation software routinely used to perform Dynamic Traffic Assignment and Dynamic Network Loading, compute performance measures of variants of road design, traffic control principles, and traffic loads.

This paper presents a discrete event simulation model that is similar to the models developed for earlier ITT studies but that also incorporates traffic modeling. This means that delays occurring due to traffic potentially have an impact on the system's performance.

3 PROBLEM DESCRIPTION

ITT is the transport of containers between terminals at the Maasvlakte 1 and the Maasvlakte 2 areas. A map of the terminals and service providers is shown in Figure 1.

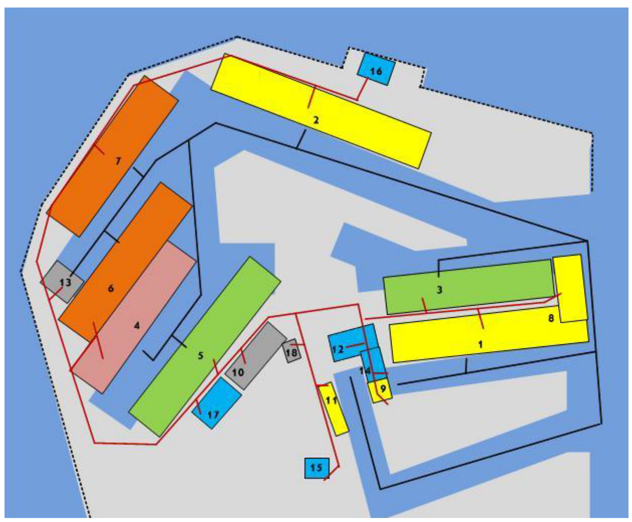

Figure 1: Map of the Maasvlakte (Jansen 2013)

3.1 Transport Infrastructure

The Maasvlakte infrastructure consists of two traffic networks, a road network (see Figure 2) and a water network (see Figure 3), which connect a total of 18 container terminals and service centers. Although the simulation model in this research is applied to the Maasvlakte area, it can be used for any possible ITT system by simply changing the network maps.

3.2 Transport Demand

The different transport demand scenarios for the ITT system have been defined by Gerritse (Gerritse 2014) as part of the "scenario definition" task of the "Inter-terminal transport on Maasvlakte 1 and 2 in 2030" project. In total there are 3 different scenarios. The annual transport demand for these scenarios has been given in Table 1.

The transport demand input for the simulation model consists of a list of container transport jobs. There is one list of container transport jobs for each scenario. These lists have been created using a computerized

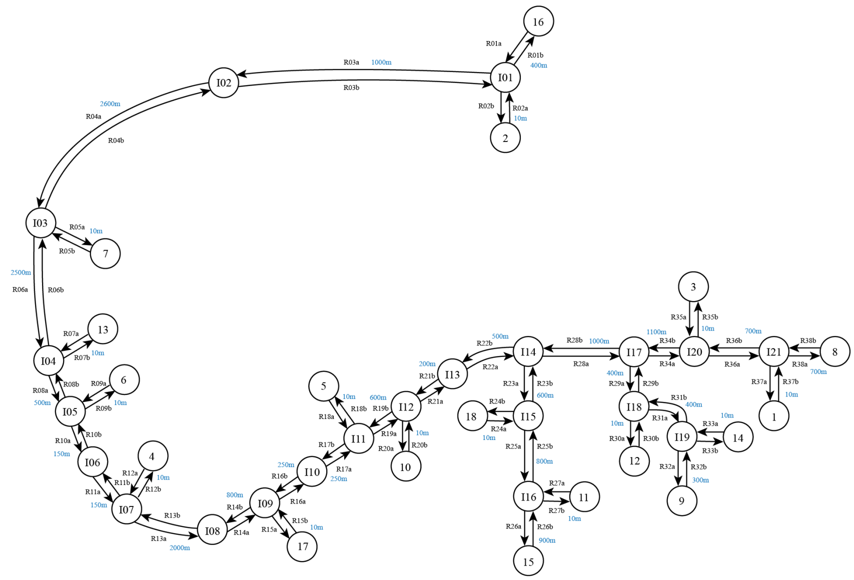

Figure 2: ITT Road Network at the Maasvlakte (Duinkerken and Negenborn 2014)

Table 1: Annual transport demand per scenario

Scenario	Annual transport demand [TEU]	Mean nr. of cont. to be transported / hour
1	3.340.000	223
2	2.150.000	144
3	1.420.000	95

demand generator. The generator, described in de Lange (de Lange 2014), is deterministic so if the input does not change it will generate the same list every time.

For each container to be transported the following data is available:

Release time	Time the container enters the system
Origin	Terminal the container needs to be transported from
Destination	Terminal the container needs to be transported to
TEU	Whether the container is 1 or 2 TEU
Due time	Latest time the container is allowed to be delivered at its destination

3.3 ITT Vehicle Configurations

A total of four different vehicle configurations per scenario has to be evaluated. The configurations comprise a number of AGVs, a number of ALVs, a number of MTSs and a combination of barges and trucks. The barges are not able to operate on their own because they are not able to reach every terminal in the system. The following types of vehicles are considered:

- Automated Guided Vehicle (AGV): The AGV is an autonomous vehicle that is used in many large container terminals to perform the transport from the quay to the stack. It is able to carry 2 TEU.
- Automated Lifting Vehicle (ALV): The (Gottwald) ALV is a rather new vehicle. In many ways it is the same as the AGV, but it has a lifting system which allows it to pick up a container from a platform. Due to this system the container transport is decoupled from the storage process, so the

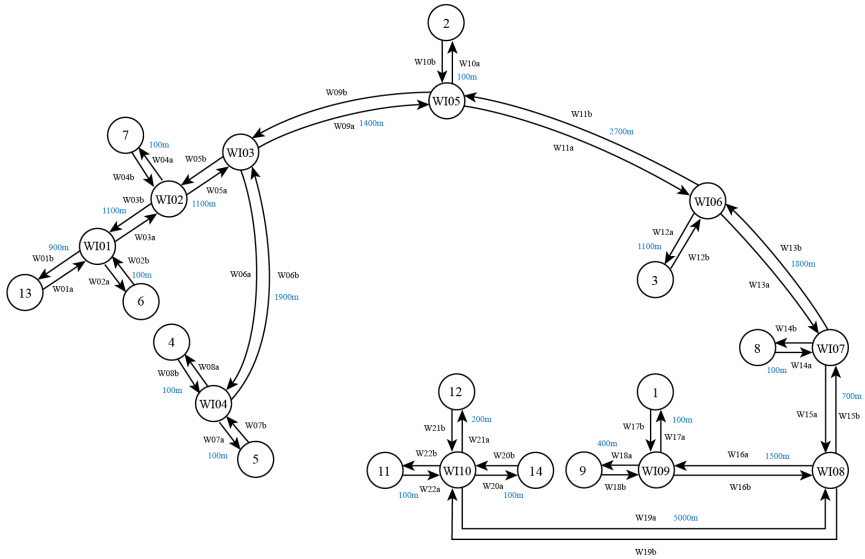

Figure 3: ITT Water Network at the Maasvlakte (Duinkerken and Negenborn 2014)

ALV and terminal equipment don't have to wait for each other to make a move. The downside of the ALV is that it is a bit heavier, and therefore possibly slower, than the conventional AGV. It is also able to carry 2 TEU.

- Multi Trailer System (MTS): A Multi Trailer System consists of a manned tractor pulling a train of terminal chassis. A tractor usually pulls 5 trailers, which gives the MTS a capacity of 10 TEU.
- Barge: The barge is the only vehicle type that does not use the closed transport route, but instead travels over water. The barge in not able to visit all terminals at the Maasvlakte, and will therefore operate alongside one of the other vehicle types. Barges can usually carry 50 to 100 TEU.
- Truck: The truck, or terminal tractor, is a manned vehicle able to carry 2 TEU. From a modeling perspective, its process is the same as for the AGV.

3.4 Performance Indicators

By far the most import task of the ITT system is to deliver the containers to their destination in time. In order to measure to what extent the system is able to perform this task, the performance indicator "non-performance" is used. If a container is delivered too late it is counted as non-performance. This method of registering non-performance is conform to the method used by Tierney et al. (Tierney, Voss, and Stahlbock 2013) and Nieuwkoop (Nieuwkoop, Corman, Negenborn, Duinkerken, van Schuylenburg, and Lodewijks 2014). Non-performance is the key performance indicator of the ITT system and will show the percentage of containers that has not been delivered in time.

Besides the non-performance, there are a number of other important performance indicators. These include the following: average time containers are being delivered too late, occupation rates of the vehicles, number of idle vehicles, loading rates of the vehicles, occupation rates of the terminal equipment, waiting times at the terminals, total distance traveled by the vehicles, total distance traveled empty by the vehicles and delays due to traffic.

4 SIMULATION MODEL

Because of the discrete nature of the ITT system, the simulation model also needs to be discrete. Therefore a discrete event simulation model was developed using Delphi and the object oriented simulation tools provided by TOMAS. A number of dispatching rules is built into the system which decide on matters like choosing the modality with which to transport a container when barges are used and requesting empty vehicles from other terminals to transport a container.

4.1 Model Overview

The simulation model is object-oriented and is operating at the container level. It consists of the following objects: Containers, Container-Generator, Roads, Intersections, Terminals, Terminal Controls, Nodes, Terminal Equipment, Vehicles, Quay Cranes and Barges. The Containers, Roads and Nodes do not have a process and are therefore passive. All other objects are active. Figure 4 shows a schematic representation of the physical objects in the model. A Terminal consists of a number of Terminal Equipment and a Container stack. Vehicles drive between the Terminals, where they are loaded or unloaded. The Vehicles drive over a network of Roads and Intersections to reach their destination. The Barges use a separate network of waterways which is connected to all Terminals with waterside operations.

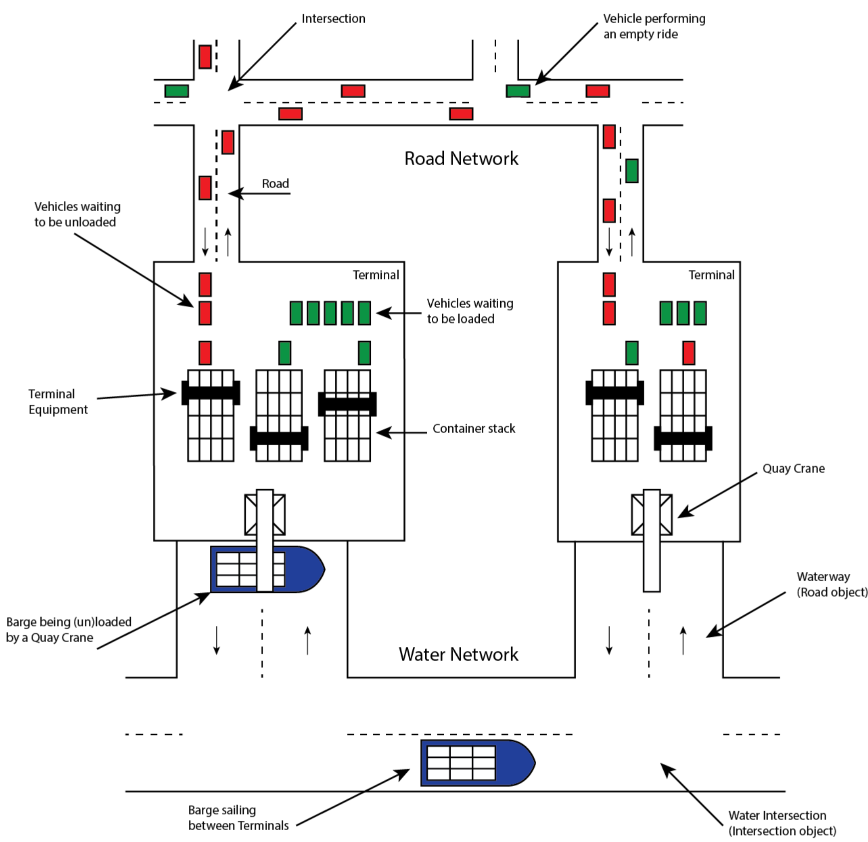

Figure 4: Schematic representation of the modeled objects

4.2 Traffic Modelling

The vehicles (AGVs, ALVs, MTSs and Trucks) and barges travel through the system over a network of nodes and arcs. The nodes represent the terminals and intersections, and arcs represent the roads. The vehicles and barges both have a separate network. They use Dijkstra's algorithm to plan their path across the networks. Thus, the routing of vehicles is done based on a shortest path principle, based on distance. In fact, the topology is such that there is always a single shortest path between any pair of points. Each terminal has its own control system which is able to request empty vehicles from other terminals to transport a container when no vehicles are available at the terminal itself. It is also used for the MTS scenarios to assign the terminal tractor part of the MTS to a trailer.

The dispatching of empty vehicles is as follows. If a terminal over a look-ahead time expectes to lack vehicles for some containers, it can issue a request for vehicles to the other container terminals. The request is only issued for the containes that are due within the look-ahead time, and have no vehicle available. For each such container, a single request for vehicle is issued. The look-ahead time used was 2 hours in the simulations. Some other terminals with excess empty vehicles can then accept this request for a vehicle, and send one vehicle to the terminal in need. Note that there is commitment of this empty rides for what concerns destination terminal; but no committment for what concerns the precise container that it has to pick up. In other terms, when the vehicle arrived at the destionation terminal, it will join the queue of available vehicle and acrry the next container handled.

Unlike previously built ITT simulation models from Duinkerken et al. (Duinkerken, Dekker, Kurstjens, Ottjes, and Dellaert 2006) and Ottjes et al. (Ottjes, Veeke, Duinkerken, Rijsenbrij, and Lodewijks 2006), the new simulation model has a built in traffic modeling system. Vehicles can experience delays at the intersections in the system. Each intersection decides which vehicle is allowed to cross the intersection first. Two different algorithms can be used to decide which vehicle to choose: a simple First-In-First-Out algorithm and a more advanced priority algorithm which considers container priority, wether vehicles are going in the same direction and wether they are able to cross at the same time without conflicts. Vehicles can also experience delays at crossings with rail or public road. These crossings have a traffic light that can be set to red or green for certain periods of time, simulating for instance passing trains.

Spill back is the phenomena by which vehicles are held back before an intersection by the traffic, as as result another interesection is blocked. We model this phenomenon as a vertical queue, as commonly done in traffic simulation. This prevents queue at one intersection to completely block the road link and block some intersection upstream.

4.3 Stochastics

Most of the variance in the workload for the ITT system is caused by the arrival patterns of ships, barges, trains and trucks. The actual schedules of monthly, weekly and daily arrivals are analyzed and based on the expected growth in the future scenario's a realistic schedule for the arrivals of these modalities is created. An exponential distribution is used for the interarrival times to introduce a random component for the arrivals of ships, trains and trucks. Another important aspect is the dwelltime of containers in the system. For the duetimes of containers an Erlang-K distribution (with k=5) is used as is suggested by the collected data. Finally, exponential distributions are chosen to model the loading and unloading times for containers to and from ITT vehicles and for the handling times of containers at the terminals.

5 RESULTS

5.1 Case definition

The simulation model described in the previous section is used to evaluate various ITT configurations. Input for the case that is simulated is extracted from the common dataset for the study of the Maasvlakte terminals as presented by Duinkerken (Duinkerken and Negenborn 2014)). This dataset defines the locations and handling capacities of the terminals, the road network for ITT with all the intersections, the characteristics of terminal handling equipment and ITT vehicles. Furthermore, three expected transport demand scenarios (with high, medium and low growth) for 2030 as defined by Gerritse (Gerritse 2014) are used. The number of ITT vehicles that are used for the various configurations is based on the outcome of the integer programming model proposed in Nieuwkoop (Nieuwkoop, Corman, Negenborn, Duinkerken, van Schuylenburg, and Lodewijks 2014). According to this model these configurations should make sure that more than 99% of the containers are delivered in time. Experiments will show if this is also the case for the more realistic simulation model.

5.2 Experiments

The runtime for the simulations has been set to 12 weeks (2016 hours). The first two weeks are used as a warm-up period and the data is for these two weeks is not reported. Instead of measuring the performance for each week individually, which would result in 10 observations, the 10 week measured performance is averaged over the complete period. Furthermore, no sensitivity analysis has yet been executed at this stage of the research. All experiments have been carried out on a HP EliteBook 8570w with an Intel Core i7 processor and 8 GB RAM.

The non-performance values for the 12 ITT configurations are given in Table 2. Table 2 shows that the ALV configurations score the lowest non-performance for all 3 scenarios. The ALVs are the most flexible of all configurations because they don't have to wait for a crane to load a container or for a full trailer that can be coupled. Therefore they operate the best without planning. However, for scenario 1 the ALV configuration still results in 18.3% of all containers not being delivered in time. The MTSs have the second lowest, and the AGVs the third lowest non-performance values. With the exception of scenario 2, these two configurations are relatively close to each other in terms of operational performance.

Table 2: Performance Indicators for the various ITT configurations

Scenario	Config	Non-perf %	Avg late [m]	Avg late cont [m]	Mean occ
1	51 ALVs	18.3	84.1	460.2	0.91
	65 AGVs	41.5	927.5	2234.4	0.97
	16 MTSs	40.7	1908.0	4690.5	0.97
	41 Trucks + 2 Barges	98.6	15468.5	15689.4	0.99
2	33 ALVs	11.2	40.9	366.0	0.95
	42 AGVs	39.4	492.9	1249.6	0.99
	12 MTSs	26.7	220.6	825.1	0.98
	22 Trucks + 3 Barges	98.5	26258.5	26650.5	1.00
3	24 ALVs	2.5	0.9	36.2	0.92
	32 AGVs	21.7	49.7	229.6	0.93
	9 MTSs	19.3	42.8	221.5	0.98
	17 Trucks + 2 Barges	98.7	20965.6	21231.2	1.00

5.3 Intersection control

For the evaluation of the ITT configurations the priority algorithm was used for all simulation runs, but it is also possible to use a more simple First-In-First-Out algorithm. Figure 5 shows the differences in vehicle delay per ride between these two algorithms. The mean ride time is about 11 minutes. All experiments have been run for scenario 3.

The results show that using the priority algorithm results in much lower vehicle delays, especially when a larger amount of vehicles travels across the network. This is because the priority algorithm can select multiple vehicles that are allowed to cross at the same time, while for the FIFO algorithm the vehicles are only allowed to cross an intersection one at a time. However, results also show that the priority algorithm does not result in a lower non-performance. In fact, it is a little bit higher. This might be explained by the fact that the priority algorithm only considers what happens within the intersection and not around it. Empty vehicles automatically get the lowest priority, so they have to wait at the intersection until all other non-empty vehicles from other directions have crossed or there is a vehicle with an urgent container behind it. Therefore it is possible that an empty vehicle has to wait for a long time while there might be a container with a high priority waiting for the vehicle at a terminal.

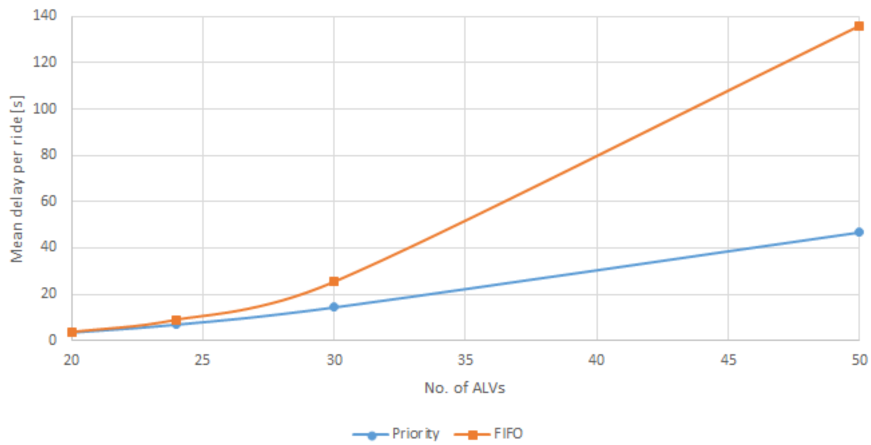

Figure 5: Mean vehicle delay per ride

6 CONCLUSIONS

This paper reports on a discrete event simulation model for determining optimal configurations for an ITT system. Four different ITT vehicle combinations are evaluated for three demand scenarios for 2030.

By far the most important performance indicators are how many containers are not delivered in time and how much too late they have been delivered. Therefore the choice of the best ITT configuration will only be based on the non-performance and the average time that containers have been delivered too late. The ALV configurations have by far the lowest non-performance and lateness values for each of the 3 scenarios. However, this can only be concluded under the currently used dispatching rules and vehicle properties. Results have shown that the vehicle speed has a big influence on the system performance, which can be explained by the large distances in the ITT system. Vehicles spend most of their time driving. In the experiments the speed of the AGV and ALV have both been set to the same value, although the current ALVs are a bit slower than the current AGVs. This difference in speed might actually make the AGVs perform better than the ALVs. Also adding a proper planning system might make the less flexible configurations perform better than they do now.

The model developed during this research is not the first ITT simulation model that has been developed, but it is the first model which incorporates traffic modeling into the ITT system. It is the first ITT simulation model where delays occurring due to traffic have an impact on the system's performance. The model is not only able to simulate delays within the system, but also delays due to crossings with rail or public road. The Port of Rotterdam expects that traffic delays will be a major problem for the ITT system.

This research has provided a discrete event simulation model for an ITT system. The model could be used to evaluate different operational aspects of the system. Also, several expansions and improvement could be thought of. It is recommended to use the simulation model to find the number of vehicles required to get a non-performance below 1% (or 0.5%, or 0.1%, etc.) for all 12 instances. Moreover, the simulation model could be used to investigate the influence of crossings with rail or public road. These crossings were not included in the evaluation of ITT configurations, but experiments showed that these crossings could have a big influence of the performance of the system. More research is needed in finding out where these intersections exactly are, what time delays they would cause, and what the effect of this would be on the system. Furthermore, for carrying out the ITT configuration evaluation simulation runs in this paper a specfici strategy was chosen on how to operate the barges. It is recommended as future researchto use the simulation model for investigating different barge routing strategies.

ACKNOWLEDGMENTS

This research is supported by the Port Research Center project "Innovative Concepts for Inter Terminal Transport on Maasvlakte 1 and 2 at the Port of Rotterdam" and partially supported by the VENI project "Intelligent multi-agent control for flexible coordination of transport hubs" (project 11210) of the Dutch Technology Foundation STW.

REFERENCES

Bish, E. K., F. Y. Chen, Y. T. Leong, B. L. Nelson, J. Wing, C. Ng, and D. Simchi-Levi. 2005. "Dispatching Vehicle in a Mega Container Terminal". *OR Spectrum* 27:491–506.

Daganzo, C. F. 1995. "The Cell Transmission Model part II. Network Traffic". *Transportation Research Part B* 29:79–93.

de Lange, L. 2014. "Generator for future inter-terminal container transport demand scenarios on the Maasvlakte 1 and 2". Technical report, Delft University of Technology, Maritime & Transport Technology.

Diekman, W., and J. W. Koeman. 2010. "Gesloten transport route: Inter Terminal Transport op Maasvlakte 1 en 2". Technical report, Projectorganisatie Maasvlakte 2.

Duinkerken, M. B., R. Dekker, S. T. G. L. Kurstjens, J. A. Ottjes, and N. P. Dellaert. 2006. "Comparing transportation systems for inter-terminal transport at the Maasvlakte container terminals". *OR Spectrum* 28:469–493.

Duinkerken, M. B., J. J. M. Evers, and J. A. Ottjes. 1999. "TRACES: Traffic Control Engineering System". In *Proceedings of the 1999 Summer Computer Simulation Conference*, 461–465. Chicago, IL, USA.

Duinkerken, M. B., and R. R. Negenborn. 2014. "Definition of common parameter values required for ITT system design". Technical report, Delft University of Technology, Maritime & Transport Technology.

Egbelu, P. J., and J. Tanchoco. 1986. "Potential for Bi-directional Guide-path for Automated Guided Vehicle Based Systems". *International Journal of Production Research* 24:1075–1097.

Evers, J. J., and S. A. Koppers. 1996. "Automated Guided Vehicle Traffic Control at a Container Terminal". *Transportation Research Part A: Policy and Practice* 30:21–34.

Gambardella, L. M., A. E. Rizzoli, and M. Zaffalon. 1998. "Simulation and Planning of an Intermodal Container Terminal". *SIMULATION on Harbour and Maritime Simulation* 71:107–116.

Gerritse, E. J. 2014. "Analysis for Inter Terminal Transportation demand scenarios for the Maasvlakte I and II in 2030". Technical report, Delft University of Technology, Maritime & Transport Technology.

Henesey, L., P. Davidsson, and J. Persson. 2009. "Evaluation of Automated Guided Vehicle Systems for Container Terminals Using Multi Agent Based Simulation". *Multi-Agent-Based Simulation* 9:85 – 96.

Incomaas 1994. "Report definition phase". Technical report, Gemeentelijk Havenbedrijf Rotterdam.

Jansen, R. 2013. "Determining the cost savings for the participants in a joint inter terminal transport system at the Port of Rotterdam". Master's thesis, Erasmus University Rotterdam.

Kim, K. H., and Y.-M. Park. 2004. "A Crane Scheduling Method for Port Container Terminals". *European Journal of Operation Research* 156:752–768.

Le, H. M., A. Yassine, and R. Moussi. 2012. "DCA for Solving the Scheduling of Lifing Vehicle in an Automated Port Container Terminal". *Computational Management Science* 9:273–286.

Liu, C.-I., H. Jula, K. Vukadinovic, and P. Ioannou. 2004. "Automated Guided Vehicle System for Two Container Yard Layouts". *Transport Research Part C* 12:349–368.

Ng, W., and K. Mak. 2005. "Yard Crane Scheduling in Port Container Terminals". *Applied Mathematical Modelling* 29:263–276.

Nieuwkoop, F., F. Corman, R. R. Negenborn, M. B. Duinkerken, M. van Schuylenburg, and G. Lodewijks. 2014. "Decision support for configuration determination in Inter Terminal Transport System design". In *Proceedings of the 2014 IEEE International Conference on Networking, Sensing, and Control*. Miami, FL, USA.

Ottjes, J. A., H. P. Veeke, M. B. Duinkerken, J. C. Rijsenbrij, and G. Lodewijks. 2006. "Simulation of a Multiterminal System for Container Handling". *OR Spectrum* 28:447–468.

Peterkofsky, R. I., and C. F. Daganzo. 1990. "A Branch and Bound Solution Method for the Crane Scheduling Problem". *Transportation Research Part B* 24B:159–172.

Tampère, C. M. J., R. Corthout, D. Cattrysse, and L. H. Immers. 2011. "A Generic Class of First Order Node Models for Dynamic Macroscopic Simulation of Traffic Flows". *Transportation Research Part B* 45 (1): 289–309.

Tierney, K., S. Voss, and R. Stahlbock. 2013. "A Mathematical Model of Inter-Terminal Transportation". *European Journal of Operation Research* 235 (2): 448–460.

van Burgsteden, M., P. Joustra, M. Bouwman, and M. Hullegie. 2000. "Modeling road traffic on airport premises". In *2000 Winter Simulation Conference Proceedings*, 1154–1163. Orlando, FL, USA.

van Schuylenburg, M., W. Stijlen, M. Stubenitsky, H. Weustenenk, and C. Pons. 2002. "Maasvlakte Integrale Container Logistiek". Technical report, Gemeentelijk Havenbedrijf Rotterdam.

Vis, I. F. A., and M. B. M. de Koster. 2003. "Transshipment of containers at a container terminal: an overview". *European Journal of Operational Research* 147:1–16.

AUTHOR BIOGRAPHIES

HERBERT J.L. SCHROËR studied mechanical engineering at Delft University of Technology, The Netherlands, from which he obtained a Master degree in 2014. He specialized in transport and logistic engineering.

FRANCESCO CORMAN is Assistant Professor at the Section of Transport Engineering & Logistics, Delft University of Technology. His research career started in Italy at Roma Tre University, he got a PhD at Delft University of Technology and Post-Doc at Katholieke Universiteit Leuven, Belgium. His research interests include optimization in discrete transport systems, railway traffic control, scheduling of discrete event systems, study of dynamics of uncertainty in transport systems. His email address is f.corman@tudelft.nl.

MARK B. DUINKERKEN obtained his Master degree in Applied Mathematics at the Delft University of Technology. He is currently an Assistant Professor in Logistic Engineering at the Delft University of Technology. His specialization is modeling and simulation of logistic processes and optimizing planning and control of logistic processes with OR-techniques. He participated in several public-private research projects aimed at the design of high capacity container terminals. Other work includes research concerning City Logistics, the development of an AGV-laboratory and the development of simulation tools. His email address is m.b.duinkerken@tudelft.nl.

RUDY R. NEGENBORN received the PhD degree in distributed control from Delft University of Technology, the Netherlands. Currently, he is an Assistant Professor in Control of Transport Technology at the Section Transport Engineering & Logistics. Rudy Negenborn's research interests include multi-agent systems, distributed control, and model predictive control, with applications in control of networked transport systems. He is editor of the books "Intelligent Infrastructures" and "Distributed Model Predictive Control Made Easy". His email address is r.r.negenborn@tudelft.nl.

GABRIEL LODEWIJKS obtained his Master degree (cum laude) in mechanical engineering at Twente University and Delft University of Technology, The Netherlands and his Ph.D. degree at Delft University of Technology on the dynamics of belt systems. He is Professor of Transport Technology and Logistic Technology at the faculty of Mechanical, Maritime and Materials Engineering of Delft University of Technology. His main interest is in belt conveyor technology, DEM applications in transport technology, automation of transport systems, material engineering and dynamics. His email address is g.lodewijks@tudelft.nl.