Proceedings of the 15th European Simulation Multiconference (ESM2001).
June 2001. Prague [SCS]. ISBN 1-56555-225-3

A SIMULATION MODEL FOR INTEGRATING QUAY TRANSPORT AND STACKING POLICIES ON AUTOMATED CONTAINER TERMINALS

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KEYWORDS

Control systems, Discrete simulation, Transportation.

ABSTRACT

In order to accommodate the growth in intercontinental container transport, port facilities have to be up-scaled drastically. One of the major challenges is to double the capacity of the marine operation on a container terminal. In this study the model of a quay transport system using automated guided vehicles (AGVs) is integrated with a detailed model of the container stack. The result is a generic, configurable terminal simulation model.

Length, width and height of the stacking area can be set, as well as the physical properties of the stacking crane, like crane speed, cat speed and hoisting speed. Different stacking policies are designed and implemented in the model. The simple policies do not require any information about the container load or destination. A more advanced policy will use available information to improve stack performance. Performance measurements show that by using these policies a significant improvement can be achieved.

From the simulation models, valuable insights can be obtained about the optimal stack height, the number of AGVs and other variables. The results of our research can be applied on the automated container terminals in Rotterdam.

INTRODUCTION

About our research

Every year there is a big growth in containerized transport throughout the world. In response to the growing demand for transportation and in order to reduce labour costs, Europe Combined Terminals (ECT) in Rotterdam has introduced a high degree of automation to its terminals. The Delta Sealand terminal (1993) was the first fully-automated container terminal.

The Dutch Centre for Transport Technology has started research on the design of a new generation of container terminals. These have to be equipped to handle the anticipated arrival of Jumbo Container Vessels with a capacity of 8000 TEU (Twenty-Foot Equivalent Units) or perhaps an even greater capacity.

Approach

The three key elements of the logistic chain at a container terminal are the quay cranes, the intra-terminal transport and the container stack. Building quay cranes with higher capacity (thus shorter cycle times) is the task of mechanical engineers. In the near future, quay cranes with a capacity of 100 moves per hour will be possible (1960: 10 moves per hour).

Such fast quay cranes require a reliable, high capacity, transport system. Although other transport systems are possible, we consider only systems using Automated Guided Vehicles (AGVs). Our earlier research presented a method for the design of multi-AGV systems and control of their operation.

The focus of this paper is on the container stack, the place where containers are stored prior to further transport. A container stack consists of an area where containers can be placed, and one or more cranes to handle them. Although this is not essential to the stacking policy, in our case the stacking cranes are fully automated. Containers must be stacked in such a way that the stacking capacity is maximized and the response time is minimized.

Stack capacity is basically the product of length, width and stacking height. The real capacity is influenced by different container sizes (20', 40', 45’ and off-standard) and individual requirements on the container position (e.g. reefers need an electric outlet for cooling systems).

Stack response time is largely influenced by the technical capacity of the stacking crane (crane speed, cat speed and hoisting speed). In addition, the most important factors are the x and y positions of the desired container and the number of containers on top of it that need re-stacking.

MODEL DESCRIPTION

General

In Figure 1 an overview of a container terminal is given. The main elements in our simulation model correspond with the physical objects: containers and containerships, quay cranes, quay transport system, stack and stacking cranes. One of the most important elements of our model however is virtual, namely the Job Control, the planning and control module.

Figure 1 Overview of a container terminal

In the next paragraphs the elements in our model are described.

Stack

The stack consists of a number of stacking lanes. A stacking lane is specified by its width and length. Each stacking lane uses its own stacking crane. The stacking lane is connected with the quay infrastructure by 4 AGV transfer points per stacking lane. Each stacking lane is divided in an export-area and an import-area. All containers for loading will be placed in the export-area; all containers that are unloaded from a ship are placed in the import-area.

The physical sizes of stacking lanes are user-defined. A percentage can be given, which designates the part of the stack that may be used for a specific ship. Because a basic principle is that containers for different ships cannot be on the same stack-pile, a number of ground positions, randomly distributed over the stacking lane, are eliminated. During the loading of a ship the stack will become emptier. To prevent the use of these positions for re-stacking, they can be blocked. They are actually intended for use for subsequent shiploads.

Automated Stacking Crane

Each stacking lane is equipped with one Automated Stacking Crane (ASC). This crane is used for both the stacking of incoming containers and the removal of outgoing containers. All movements of these cranes are considered constant, (no acceleration or deceleration) and are serial. Before a crane moves in the length of the stacking lane, the container load is hoisted to the maximum height, then the cat moves to the middle position, before the automated ASC travels further. The hoisting height is determined by the maximum stacking height. The stacking crane will always hoist a load above this maximum when travelling. The hoisting speed is considered constant, and is the weighted average of hoisting speed with and without loads.

The stacking crane provides for both the stacking of incoming load containers and the removal of outgoing ones. The stacking has priority, because this move will free an AGV. The sequencing of jobs is determined by the Job-Control, which is identical to the job-control reported earlier (Duinkerken and Ottjes 2000).
Usually, the stacking crane becomes active at the moment that an AGV arrives. Improvement can be achieved when the crane can anticipate the next move. When an ASC is idle, it can prepare for the next expected move. If the next move is inbound, the ASC travels to the AGV transfer point; when the next move is outbound, the crane travels to the stack position of the expected next container.

The ASC uses a fixed, user-defined time to pick up and release a container in a stack position. In addition, some time is needed for the acceleration and deceleration of the crane and for hoisting movements. The sum of all these times is assumed to be constant at 30 seconds per move.
The performance of the stack is called the stack response time. This is the average time the stack will handle a container request. The performance can be subdivided in average movetime inbound and average movetime outbound.

Quay cranes, ships and quay transport

The quay transport model is described comprehensively in (Duinkerken et al. 1999). Quay transport uses Automated Guided Vehicles (AGVs) for the pick-up and delivery of containers at the quay cranes. Our earlier research presented a method for the design of multi-AGV systems and control of their operation.

Two types of containers are distinguished. Unload-containers are containers on a ship that are unloaded by the quay crane and stacked in the importstack. Load-containers are defined as the containers that start in the stack, and are loaded onto a ship.
The model defines a shipload as a set of holds. Each hold defines a set of unload-containers and a set of load-containers. For each hold the quay crane that will handle the loading and unloading is pre-defined.

Within a ship hold, the loading sequence for the load-containers is determined by the load plan. This plan takes into account the destination of a container and various other properties including size, and weight. In our research we investigated the possibility of relaxing the load plan by introducing ‘load categories’. Instead of a fixed sequence of individual containers, the containers are grouped in categories, and a fixed sequence remains only between the categories. We expect that the resulting freedom of sequence within a category will improve both the quay transport and the stack response times.

Performance indicators

The performance indicators are calculated from the output of the simulation model. The main performance indicators are:

- Quay Crane utilization : percentage of time that the QC is active (= complementary to the time that the QC is waiting for AGVs)
- Re-stack % : percentage of the export containers that need re-stacking.
- AvgMove : average time the ASC uses for 1 move (inbound and outbound); also referred to as stack response time.
- ASC utilization : percentage of time during which the stacking crane is active.

STACKING METHOD : DETERMINE LANE

General

A distinction is made between the stacking method and stacking strategy. The stacking method relates to the choice of a stacking lane (and thus of a stacking crane). The stacking strategy relates to the choice of a position within a stacking lane. Both choices are made separately, and not necessary at the same time. First the stacking method determines the stacking lane, and only when the container is about to be moved inbound, is the stack position chosen.

1. Random

The simplest way to choose a stacking lane is by a random draw. The only criterion is the availability of at least 1 stack position (inbound), or at least H positions inbound, were H stand for the maximum stacking height. The latter is because extra positions are needed in case it is necessary to reach the lowest container of a stack pile.

Unload-containers originate from a ship at the quay. When the quay crane unloads a container from the ships and puts it onto an AGV, the stacking lane is chosen and this determines the destination of the AGV. Load-containers are destined for the ship. In the simulation model, all export containers are generated at the initialization time, and placed in the stack. There is no modelling of late arrivals (containers that arrive in the stack during the loading of the ship).

2. Dedicated stacking lanes

An alternative method is the assignment of stacking lanes to quay cranes. Each quay crane is serviced by one or more pre-determined stacking cranes. This method requires that the load plan be known at the moment that stacking starts. In practise, this rule is not used because of this limitation.

STACKING STRATEGY : DETERMINE POSITION

Unload containers in the import-area

All the inbound containers are placed in the import-area of the stack. The positions are randomly selected. A stacking strategy for this group of containers is of little use in this research, because further container movements, like the transfers to the landside, are not under consideration. Of course the distance between the AGV transfer points and the container position does influence the stack move time.

Initialization export-area

The export-area is initialized at the start of the simulation. All load-containers are placed in this area. The following rules apply:

- All containers are generated at the start of the simulation. They are placed in the stack according to a random pattern, representing the randomness of the arrivals of containers in the stack.
- During the initialization of the stack the ground positions for the ship are assigned. Only these positions can be used. The fill-percentage of the stack is thus the result of the user-defined physical sizes (length, width and maximum height) and the usable percentage of this space.
- If information is needed for the stack strategy, a random draw will be used to determine whether information is available for each container. A default strategy, which requires no information, must be available.

Re-stacking of container

During simulation, re-stacking is necessary if the desired container is blocked by one or more containers on top. The top-containers need to be assigned to a different stack position within the same stacking lane. The strategies for this assignment may be the same as the strategies for the generation of the export stack.

Re-stacking can be done in two ways. Reactive re-stacking means that the re-stacking move for the top-container starts at the moment that the lower container is needed for loading. This will cause a longer response-time for the stacking crane. Pro-active stacking happens during the idle times of the stacking crane, anticipating the future loading moves. In principle, pro-active re-stacking can reduce the stack response times.

In the case of loading based on categories, there is an alternative to re-stacking. If the top container is from the same category as the lower container, it is sufficient to switch the containers in the load sequence. The need for re-stacking will thus disappear.

Strategies for choosing stack positions

Several strategies for calculating a stack position have been designed and implemented. The strategies that do not require any information on the container or load plan are used as a

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benchmark, to evaluate the other strategies. A number of strategies are presented below.

1. Random

This strategy uses no information on the container or load plan. A random position is drawn, until a position is found where the container pile has not reached its maximum height.

2. Levelling

This strategy uses no information on the container or load plan. The stack is filled layer by layer. First all free ground positions (starting at the transfer points), followed by layer 2, and subsequent layers. The maximum actual stack height will be minimized.

3. Closest position

This strategy uses no information on the container or load plan. The closest position in which the pile is not maximal is chosen. During initialization of the export stack the positions closest to the AGV transfer point are chosen. During re-stacking, the free positions are sought first in the cat-move direction and then in the ASC-drive direction.

4. Maximum RSC

This strategy needs information on the load category of a container. Whether or not this information is available is determined by a random draw. Containers with no information are placed in a separate part of the stack.

If the load category is known, the preference is to place containers on top of containers of the same or a higher category for the same quay crane, in such a way that the reduction of the Remaining Stack Capacity (RSC) is minimal. The RSC of a stack position (i, j) is defined as:

$$RSC_{ij} = (H-h_{ij})^{*}\, c_{ij}$$

where
H = maximum stack height
h_{ij} = actual stack height at this position
c_{ij} = category top container at this position
(C, if top-container = none)
C = maximum number of categories

Figure 2 gives an example. Assume that a container of category c_2 will be placed on a container of category c_{ij}. The reduction in RSC, which must be minimized, leads to following formula:

$$\text{MIN} [\ (H - h_{ij}) \times (\ c_{ij} - c_2) + c_2\ ] \quad \text{for all (i, j) with } h_{ij} < H$$

Because the aim is to minimize the reduction of the remaining stack capacity, from the above it can be deduced that there is a preference for:

- the highest positions
- the smallest differences in category

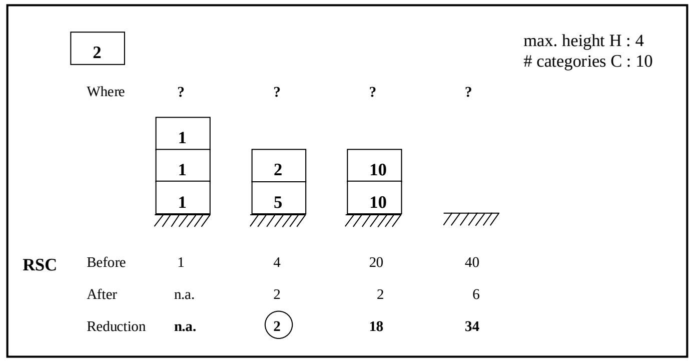

Figure 2 Example of calculation of the Remaining Stack Capacity (RSC)

If no position is available on a lower or the same category, the container is placed in such a way that the increase in RSC remains minimal. The stack position is marked for re-stacking. By doing this, a 'reversed pile' will be created, which will be usable when re-stacked.

The priority for placing containers in the stack is thus as follows:

- On top of containers for the same quay crane, of the same or a higher category.
- On top of containers for the same quay crane, of a lower category.
- Randomly.

EXPERIMENTS AND RESULTS

Sensitivity analysis of the integral system

First a range of experiments was conducted to determine the variances in the results of the simulation model. The focus was on the main performance indicator, namely the variance in the average utilization of the quay cranes.

Figure 3 shows the results for 10 different configurations. Both the load sequence (strict or by categories) and the stack strategy are varied. The RSC100 strategy is the RSC strategy with 100% information available, the RSC50 strategy is the RSC strategy with 50 % information availability. Each run has 25 replications, and the runtime is based on the complete handling of one container ship (4000 moves).

Compared to the random stack strategy with strict loading, both the RSC stack strategy and the category-based loading lead to an improvement of 5% in quay crane utilization. The effects seem to be independent and thus cumulative: when both are combined a total improvement of 10% is reached.

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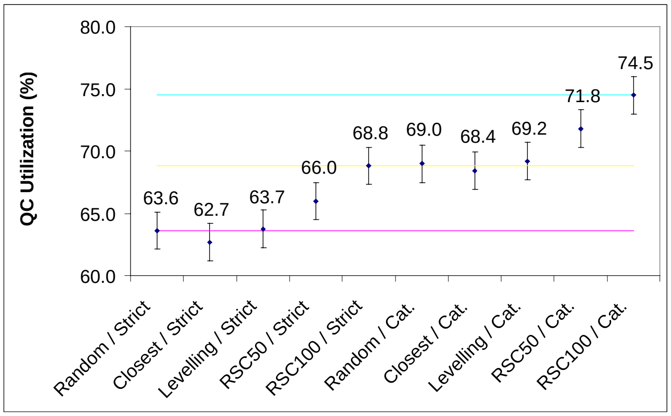

Figure 3 Results of the sensitivity analysis

Detailed results of reference runs

From the 25 replications used for the sensitivity analysis, one was chosen with which to study the results more closely. The results of these runs are presented in Table 1.

Configuration	% Re-stack	Load Move	Unload Move	Average Move	% ASC Active	% QC Active
Random / Strict	120.2	178.5	158.7	168.6	38.9	**63.6**
Closest / Strict	118.5	177.6	157.9	167.7	38.0	**62.6**
Levelling / Strict	116.4	173.7	156.9	165.3	38.3	**64.0**
RSC50 / Strict	82.6	144.4	156.6	150.5	36.4	**66.6**
RSC100 / Strict	46.7	119.2	157.7	138.5	34.9	**69.2**
Random / By cat.	115.0	175.8	157.3	166.5	41.8	**69.4**
Closest / By cat.	120.2	179.9	156.9	168.4	42.3	**69.4**
Levelling / By cat.	109.0	169.6	157.6	163.6	41.4	**70.0**
RSC50 / By cat.	64.0	132.4	158.8	145.6	38.4	**72.5**
RSC100 / By cat.	5.8	94.3	158.0	126.2	34.5	**74.9**

Table 1 Results of reference runs

The great decrease in the number of re-stacking moves when the RSC strategy is used is remarkable. This results in a substantial reduction in the average outbound move time. Because the inbound containers are placed in a separate part of the stack, the import stack, and no re-stacking moves are required there, the average inbound move time does not vary in these 10 variants. The improvement in quay crane utilization is thus completely due to faster stack response times during loading.

From Table 1, the two most important factors can be noticed, namely strict loading versus category-based loading, and random stacking versus the RSC100 stack strategy. Both effects are presented in Figure 4.

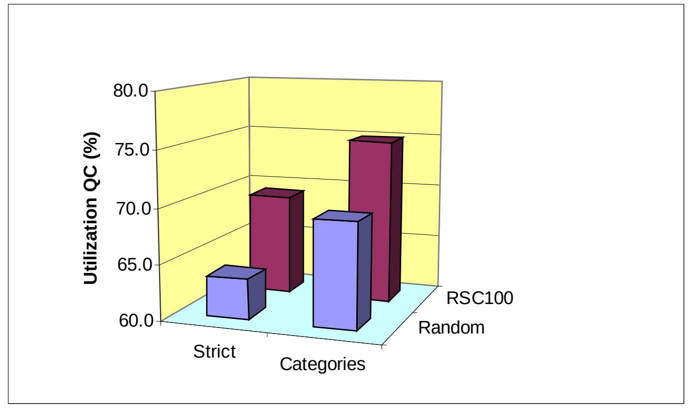

Figure 4 Effects of load categories and stack strategy

Re-stacking Strategy

During loading the need for re-stacking may arise. A re-stacking strategy is needed in order to find a new stack position for a container causing a blockage. During the reference runs, the 'closest' strategy is used. Figure 5 shows the results when other strategies are applied for re-stacking.

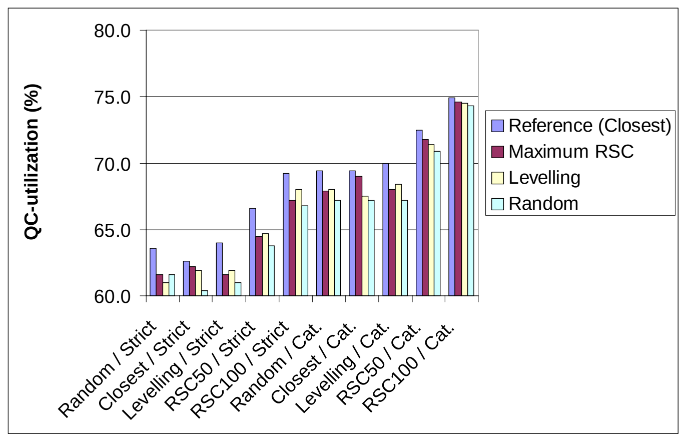

Figure 5 Effects of the re-stacking strategy on the overall performance

The results show that the 'closest' strategy for re-stacking leads to the best results. This is probably due to the high fill-percentage of the stack in the reference runs (78%). With a high fill-percentage the number of free stack positions is small, and apparently the optimal choice is to select the closest available stack position for re-stacking. However, the differences in the resulting QC-utilization are small; 2 to 3% at most.

Maximum stack height

The maximum stack height is one of the parameters that has the biggest influence on the total stack capacity. Obviously, for given length and width of the stack area, the capacity is determined by the stack height. However, the stack height influences the logistic performance indirectly too: the higher the stack piles, the greater the possibility of a container blocking another one, and thus the need for re-stacking.

In our experiments, we chose to keep the width of the stack area and the fill-percentage constant. A higher stack means a shorter stack, and thus a reduction in the travelling distances of the stacking crane.

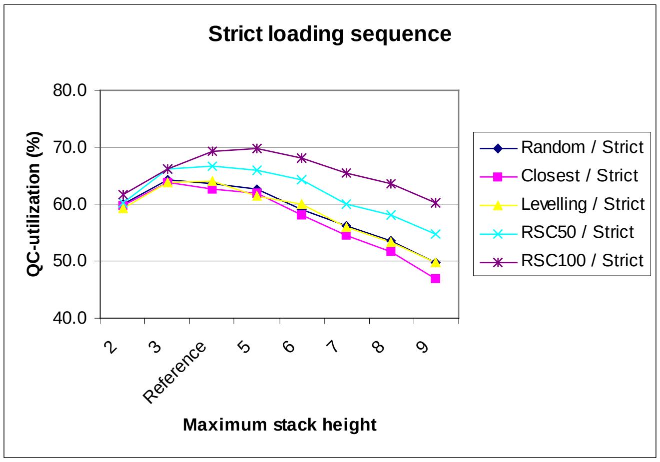

Figure 6a Effects of maximum stack height on the performance with category-based loading

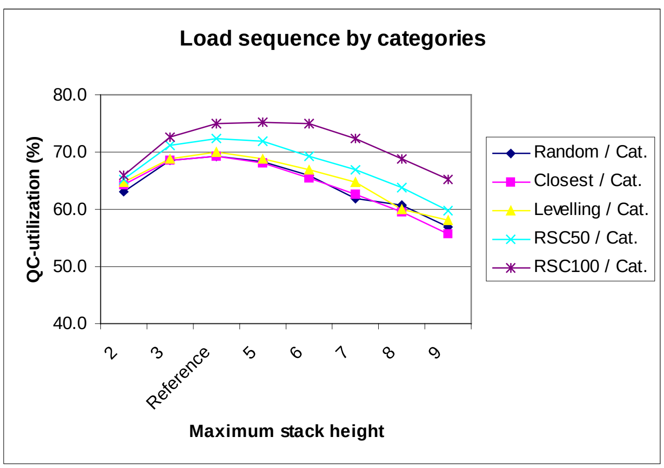

Figure 6b Effects of maximum stack height on the performance with category-based loading

The results of the experiments are given in Figure 6. Given a certain QC-utilization percentage the RSC stack strategy allows higher stack heights than the random strategy for both strict and category-based loading. The optimal stack height in our experiments was 5 containers. The decrease in performance when higher stack heights are used was smaller with the RSC-strategy than with the random strategy.

Number of AGVs in the transport system

Earlier research (Duinkerken and Ottjes 2000) has shown that the most important factor for the performance of the total system is the number of AGVs within the system. A number of experiments have been done in which the number of AGVs varied. The results are found in Figure 7.

It is obvious that using more AGVs will lead to better QC-utilization. With loading by category, a higher performance can be reached. With more than about 50 AGVs, the performance will slowly decline, probably due to congestion in the quay area.

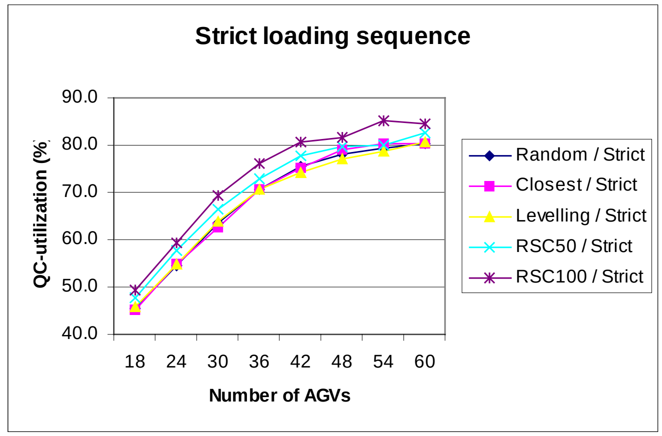

Figure 7a Effect of the number of AGVs on the performance with strict loading sequence

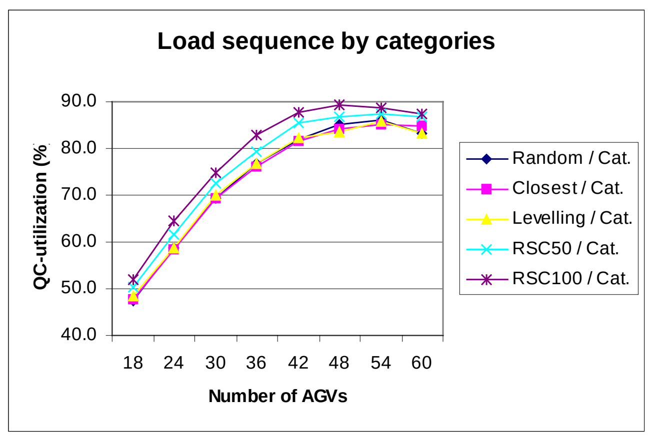

Figure 7b Effect of the number of AGVs on the performance with category-based loading

Dedicated stacking lanes

The default stack method is random; the stacking lane for each container is selected by a random draw. An alternative method is the use of dedicated stacking lanes: the containers moving to and from a specific quay crane are assigned to one or more pre-selected stacking lanes. In this way, a stacking lane will only serve one quay crane. The results of these experiments are given in Figure 8.

The improvement in quay crane utilization is small; with strict loading 2 or 3%, with loading by category 1.5%.

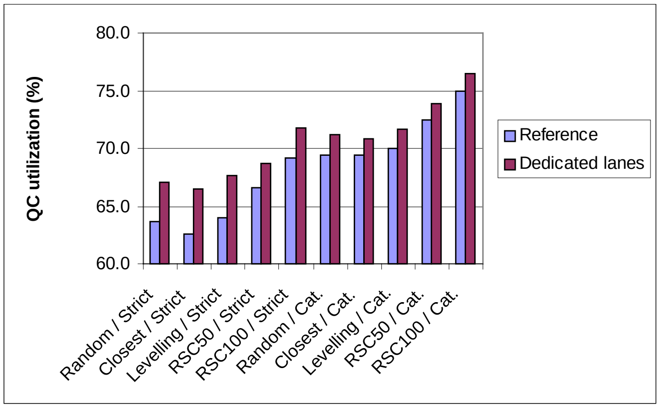

Figure 8 Results when using dedicated stacking lanes

CONCLUSIONS

Integrated model

The integrated model is based on, and an extension of our earlier research models. A model for the study of a container stack, using different stacking methods and strategies, has been integrated with previous models of the quay transport, the quay cranes, the container ships and the container terminal planning and control algorithms. This model appears to be suitable for the evaluation of a large range of different scenarios.

Without doubt, the most important part of the integrated model is the terminal planning and control program. For a more detailed study of subsystems like the quay transport, or the container stack it is possible to attach different simulation models.

Sensitivity analysis

The sensitivity analysis shows small deviations in the main performance indicators of the simulation runs. This allows us to compare the outcomes of a large number of simulation runs with different configurations and parameter settings.

Strict versus category-based loading

Earlier research has shown a large difference in performance between strict loading and totally free loading sequences. The experiments with our model that are presented in this paper give a third option, this being loading by category. The improvement in quay crane utilization is significant in comparison to strict loading and in the reference runs is about 5%.

Random versus RSC strategy

If information regarding the load plan is available during the stacking of containers, a better performance of the overall system can be reached. The RSC-strategy presented in this report shows a significant improvement when there is either partial (50%) or complete information availability. With complete information in the reference runs the quay crane utilization increased about 5%. This improvement is completely due to a shorter average stack response time during loading.

Re-stacking strategy

The influence of the strategy used for re-stacking is small. This is probably caused by the relatively high fill-percentage of the stack in our reference runs.

Stack height

In addition to the fact that higher stacking uses less space, it also results in shorter travelling distances for the stacking crane. The optimal stacking height in our research was 5 containers, but the model also allows us to investigate other configurations. Of course, in our logistic research, we do not address the issues concerning the physical and mechanical constraints of the equipment used or the infrastructure.

Number of AGVs

The relationship between number of operational AGVs and the utilization of the quay cranes has already been shown in earlier research. This paper extends this relationship by adding a more detailed and realistic model for the container stack. The outcomes are identical: a higher number of AGVs improves the performance, until a maximum is reached; more then circa 42 AGVs gives no improvement.

Dedicated stacking lanes

According to our results, it is not necessary to dedicate stacking lanes exclusively to a specific quay crane. From the experiments with dedicated lanes it has been concluded that the improvement is small. In practice, the information that is required for this method is often unavailable when it is needed.

RECOMMENDATIONS

Our integrated model (quay cranes, quay transport and container stack) allows us to model the existing automated container terminals in Rotterdam. This model can be used to improve the performance of the terminal with use of the existing equipment. It is important to find out the theoretical maximum performance of the terminal. One of the challenges is to develop an algorithm for proactive re-stacking.

In this research the simulation run-length is defined as the complete unloading and loading cycle of one container ship. The measured performance is the average over this run length. In reality, there are different situations at the start of the ship handling (when the fill-percentage of the stack is at its highest) and the end. This dynamic effect and the effect of a stack being used by more then one ship during a day should be researched in more detail.

There are many of designs for alternative layouts to define the routing in the quay transport area (Evers et al. 1998). Even dynamic routing is an option. The integrated model can be used to estimate the value of these alternatives.

Currently, the developed simulation models are redesigned and programmed in a Windows environment, using Delphi and the simulation package TOMAS (Veeke and Ottjes 2000). The result will be a distributed network of cooperating simulation models for quays, stacks, AGV system and shiploads, and in the future models for other transport modalities like barge, rail and truck service centers.

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