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# IMPROVING QUAY TRANSPORT ON AUTOMATED CONTAINER TERMINALS

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## 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 increase 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 used to deduce logistic principles for the design of a terminal layout and the operational control, and to assess the performance of the set-up by using simulation. It is focused on the transport between the deep-sea quay and the marine stack during the loading operation, being critical in the process. The key question is whether the proposed set-up is capable to produce the desired throughput.

The study has lead to two new designs, the ‘circulation layout’ and the ‘crossover layout’. Simulation shows that under simplifying assumptions the quay transport in both layouts satisfies the requirements. The performance of the ‘crossover layout’ is better and requires a considerable smaller number of AGVs.

## 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-Feet 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 (see [1], [2]). Furthermore, a simulation model, including planning and control algorithms is reported in previous papers ([3], [4]).

The focus of this paper is on improving the productivity and accuracy of the quay transport system. After analyzing the bottlenecks in the existing terminal layout, some basic principles for both the layout and the logistic control are formulated. These principles are used to define two new layouts for the quay transport system.

The influence of some of the proposed design principles is determined by using simulation. Further, the simulation runs are used to calculate the logistic performance of each of the proposed layouts. These performances can be compared with the performance of the traditional layout.

## THE AUTOMATED CONTAINER TERMINAL

### DESCRIPTION

In Figure 1 an overview of an existing container terminal is given. Containers are stacked in a large stacking area. Fully automated cranes services this stack. The quay transport is provided by Automated Guided Vehicles (AGVs), using fixed routes (further referred to as

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'layout'). Quay cranes load and unload the container vessels.

*Figure 1 Overview of a container terminal*

**QUAY TRANSPORT**

The purpose of the quay transport system is to transport unloaded containers from the ship to the stack, and to bring loadcontainers from the stack to the quay cranes. The AGVs are driving along fixed paths. The layout of the terminal in Figure 1 is shown in Figure 2. It includes 7 quay-cranes (QCs), 32 automatic stacking cranes (ASCs), a stack for empty containers, and the current routing of the AGVs. On this terminal a maximum of 50 AGVs is in operation.

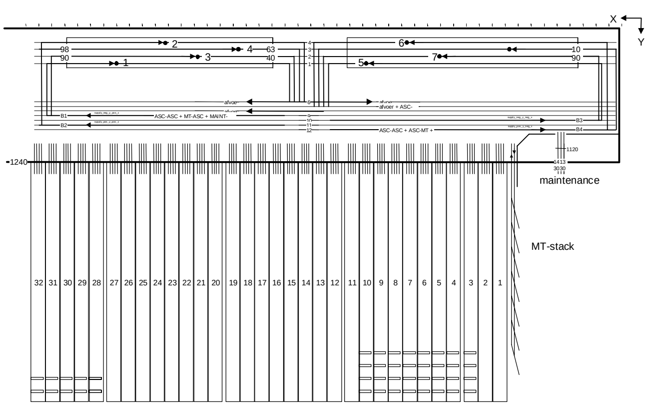


*Figure 2 Layout of the DSL terminal at the Maasvlakte Rotterdam*

The traffic between stack and quay follows a circular pattern. Typically, the vehicles travel along the entire length of the ship and turn back along the stack. In the quay area a fixed traffic lane is reserved for each quay crane. In the stack-area the traffic for two quay-cranes is combined to form a single traffic lane.

**ANALYSIS OF BOTTLENECKS**

Analyzing the operation of the quay transport system using the layout in Figure 2 results in the following summary of bottlenecks in the performance of the container terminal. These are:

- fixed routes, no flexibility
- to much crossings of routes
- parallel traffic lanes are close to each others, so that turning AGVs are hindering adjacent lanes
- stack transfer point only accessible from one side leads to waiting
- no possibilities for changing sequence of AGVs.

Quantitative analysis shows that the current transport system appears to result in long transport times and large deviations in transport times.

## IMPROVING THE QUAY TRANSPORT

**DEFINING NEW DESIGN PRINCIPLES**

The logistic performance during the loading of a jumbo container vessel is crucial. The loaded AGVs must arrive under the quay crane at the correct time, in the correct sequence and with the correct orientation. On the basis of a qualitative logistic analysis, several design heuristics are formulated:

- Designing a terminal layout, take the loading process of the ship as the critical operation.
- When loading, provide parking places for loaded AGVs close to each quay crane, serving as a buffer.
- Where possible use separate routes for loaded and empty AGVs.
- Provide for non-blocking waiting of AGVs at crossings and junctions.
- Give each quay crane its own stack partition with at least two stacking lanes per crane.
- Split-up the stack into import and export sections, the export stack close to the quay.
- Keep the scheduling adaptive, online with the progress of the transhipment process.
- Provide for a stringently controlled anticipatory, adaptive vehicle and traffic guidance.

**STACK TRANSFER POINTS**

The stack transfer points are the 'parking places' for AGVs to be loaded and unloaded at the stack. The containers are handled over the front; four places on the platform can be served. In the existing layout, the transfer points can only be reached from 1 side; incoming and leaving traffic are crossing.

Figure 3 shows a new layout for this frontal transhipment with four service points.

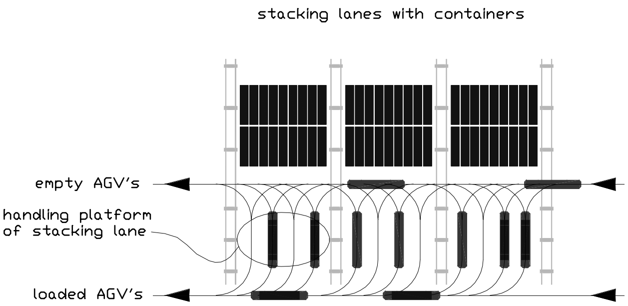


*Figure 3 Layout for transhipment over the front.*

Special in this layout is the separation between arrival and departure trips, implying that empty and loaded AGVs do not impede each other. Special measures must be taken to avoid collision between stack crane and AGVs.

### AGV BUFFERING AT QUAY CRANES

Container ships require a strict loading sequence and therefore the sequence in which the containers must arrive under the quay cranes. This sequence is generated by the so-called loading plan. This plan may be completely rigid or may permit variations within defined limits. The procedures on the level of 'scheduling and matching' must translate this into accurately timed transport orders. Even so it may be necessary to correct the sequence during the movement in order to respond to disturbances. When the AGVs on QC-platform park in parallel lines, they can be called up randomly. In this case it is possible to combine the uncoupling and sequencing. If the AGVs are parked sequentially this is not possible. Then sequencing must be done during the trip, which complicates the control and introduces disturbances.
One of the two proposed layouts (the crossover layout) uses parallel parking at the quaycrane.

### PRE-POSITIONING IN STACK LANES

Export containers are containers which must be loaded on a ship. At the arrival of an export container at the terminal, the container is placed in one of the stack lanes of the stack. Normally, this is based only on the availability of stacking positions. However, it seems possible to deduce a 'stacking plan', where, corresponding to the bays of ship to be handled, the 'logistically best' stacking lane(s) for the containers is 'pre-positioned'. According to the principle 'minimise the number of conflicting traffic crossings' the best stacking lane corresponds directly to the bay (and quay crane) positions.

In contrast to this, when the arriving containers are placed randomly on the export stack and the loading-plan is generated without taking into account the stack positions, then the containers have to be randomly called from the stacking lanes. The effects on the performance of the terminal are studied for various degrees of favourable positioning.

### TRAFFIC CONTROL SYSTEM WITH TRACES

The task of the traffic control system is to instruct individual vehicles with respect to their destination (or mission) and routing, to control conflicting common use of traffic infrastructure and to provide facilities for communication between the 'control centre' and the vehicles. TRACES has been developed as such a traffic control system. Important requirements were robustness, the power to support 'high performance control', to cope with high traffic intensities at any scale and to take into account the vehicle characteristics. The concept of TRACES is based on the use of semaphores (see [5], [6]). The traffic control system is described in [2].

## NEW QUAY LAYOUTS

### GENERAL

Based on the principles described in the previous chapter, two new terminal layouts are proposed. The existing terminal layout will allow 4 quaycranes to service a ship simultaneously. Anticipating jumbo container vessels, which are longer, the new designs will allow 6 quaycranes per ship.

Both proposed designs are using more 'quay length', due to the fact that the ships are longer and are handled by more quaycranes simultaneously (6 instead of 4). However, the width of the quay area used for the quay transport, is similar to the quay use of the existing layout. This is important because this infrastructure is expensive.

### CIRCULATION LAYOUT

Like the current layout, the stack-quay traffic follows a circular pattern. Typically, the vehicles travel along the entire length of the ship and turn back along the stack. After this, they return to the quay. In the quay area, a fixed traffic lane is assigned for each quay crane.

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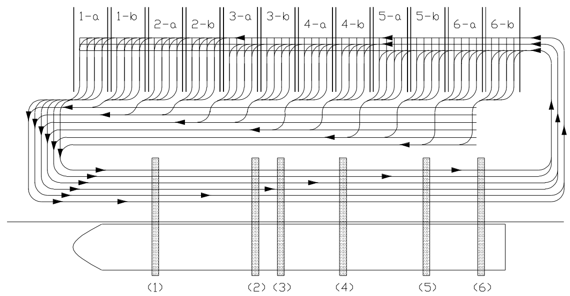


*Figure 4 Topological model for circulating quay traffic during loading.*

Figure 4 shows a topological model of the layout for circulating quay traffic during ship loading. Part of the layout is the stack configuration of Figure 3. Each QC more or less has its own circuit. Only in the front of the stack there is some crossing traffic. The set-up of the transition control is such that the number of crossings is reduced as much as possible. In the layout of Figure 4, for returning empty AGVs two tracks are available. However simulation shows that three tracks are necessary; the simulation results reported are based on this improvement.

### CROSSOVER LAYOUT

In the unconventional 'crossover' layout, the AGVs drive between the rear legs of the crane to be served. Figure 5 gives the routing of the quay-traffic during the loading operation, where the size of the AGVs and their manoeuvering possibilities carefully are taken into account.

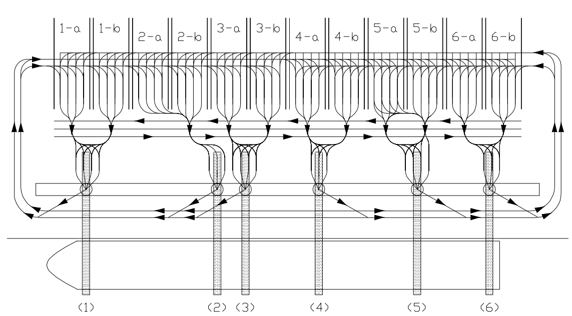


*Figure 5 Topological model of the quay-traffic for the 'crossover' layout*

Part of the layout is the stack configuration of Figure 3. For each quay-crane there are four parking places for AGVs, situated directly at the rear legs. The AGVs on these parking places can be send to the quaycrane for the handling in any order. In the layout there are three lanes for the traffic running parallel between the rear legs of the quaycranes and the stacking lanes. However in the simulation study the middle lane is not used for the traffic; in practice one may think of a special lane for backup and recovery.

## SIMULATION RUNS AND RESULTS

### DEFINITION OF THE PERFORMANCE INDICATORS

The objective of the simulation is to study the effects of factors like the terminal layout, the degree of pre-positioning of containers on the stack, the speed of the AGVs and the sequencing of containers during loading on the performance. More specific we like to answer the question: is the proposed layout in combination with the control able to support the loading operation, satisfying the logistic requirements?

The performance indicators are calculated from the output of the simulation model. For the purpose of this paper, the following performance indicators are presented:

- Quay Crane utilization : percentage of time that the QC is active (= complementary to the time that the QC is waiting for AGVs)
- Sequence Error ratio: number of sequence errors made during loading, as ratio of the total number of loaded containers. The supposition is that a strict loading sequence is desired.
- Number of AGVs : number of AGVs that is needed to support the transition. This 'N' is minimal in the sense that an additional AGV does not increase the QC-utility-% nor decreases the sequence error ratio more than 0.05 and, in addition, that one AGV less will decrease the QC-utility and/or increase the sequencing error-rate.

### SET-UP OF THE SIMULATION

The main elements in the 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 the model however is virtual, namely the Job Control, the planning and control module.

The developed simulation model is programmed using Delphi and the discrete event simulation package TOMAS (see [7]). More detail on the simulation model used is found in [3].

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# RESULTS

## CIRCULATION AND CROSSOVER VERSUS TRADITIONAL LAYOUT

Table 1 shows results for both the circulation layout and the crossover layout. The AGVs are driving 4 m/sec. In these cases sequencing is only promoted (but not forced) by timing the departures from the stack. The focus lies purely on the quay transport as such and therefore the times of coupling of the spreader (i.e. the hoisting yoke) is neglected and also the special positioning of the AGV as is the case in the crossover layout.

| **Production** | **Circulation layout** | | | **Crossover layout** | | |
|---|---|---|---|---|---|---|
| moves / hour | util% | #agv | sqEr | util% | #agv | sqEr |
| 20 | 100.0 | 40 | 0.24 | 99.8 | 28 | 0.09 |
| 40 | 100.0 | 46 | 0.26 | 99.8 | 34 | 0.08 |
| 60 | 99.9 | 52 | 0.30 | 99.6 | 40 | 0.08 |
| 80 | 99.9 | 64 | 0.21 | 99.9 | 46 | 0.06 |
| 100 | 99.6 | 76 | 0.20 | 99.7 | 54 | 0.06 |
| 120 | 97.1 | 88 | 0.32 | 97.2 | 58 | 0.21 |

*Table 1 performance of circulation and crossover layouts*

To put these results into perspective, with the existing layout the maximum measured performance of the system (during 1 hour) is 35 moves per quaycrane. The results in Table 1 suggest that doubling or tripling the quay transport capacity is possible.

## AGV-SPEED

Using a AGV that is operating at a lower speed will of course result in the need for more AGVs. More AGVs however will increase the probability of traffic congestion. Table 2 shows the same cases as in the previous chapter, but with a lower AGV speed. Slow AGVs are driving 2 m/sec.

| **Production** | **Circulation layout** | | | **Crossover layout** | | |
|---|---|---|---|---|---|---|
| moves / hour | util% | #agv | sqEr | util% | #agv | sqEr |
| 20 | 99.7 | 40 | 0.36 | 99.5 | 28 | 0.14 |
| 40 | 99.9 | 52 | 0.30 | 99.3 | 34 | 0.16 |
| 60 | 99.4 | 70 | 0.20 | 99.7 | 46 | 0.11 |
| 80 | 90.5 | 76 | 0.52 | 99.3 | 58 | 0.18 |
| 100 | 75.4 | 82 | 0.80 | 86.7 | 64 | 0.94 |
| 120 | 65.1 | 94 | 1.38 | 69.4 | 72 | 1.81 |

*Table 2 performance with slow AGVs*

As expected, more AGVs are needed to achieve the necessary performance. With the circulation layout, lower production can be achieved, due to congestion. The crossover layout outperforms the circulation layout.

## SEQUENCE FORCING

The effects are studied when the control system forces strictly sequencing. The results are shown in Table 3. As expected sequencing errors are eliminated at the expense of QC-utilisation. Again these cases are purely focussed on the quay transport.

| **Production** | **Circulation layout** | | **Crossover layout** | |
|---|---|---|---|---|
| moves / hour | util% | sqEr | util% | sqEr |
| 20 | 100.0 | 0.00 | 99.8 | 0.00 |
| 40 | 100.0 | 0.00 | 100.0 | 0.00 |
| 60 | 100.0 | 0.00 | 99.8 | 0.00 |
| 80 | 99.7 | 0.00 | 99.9 | 0.00 |
| 100 | 91.9 | 0.00 | 99.1 | 0.00 |
| 120 | 77.5 | 0.00 | 94.3 | 0.00 |

*Table 3 performance with strict sequencing*

When a strict load sequence is forced, the performance of the circulation layout drops heavily. The crossover layout still performs well; this is obvious caused by the fact that this layout employs four parking places for AGVs at each quaycrane.

## PRE POSITIONING

The effect of pre-positioning of containers in the stack lanes is studied in combination with fast AGVs and a strict loading sequence. The results are presented in Table 4 and Table 5.

| **Production** | **0%** | **25%** | **50%** | **75%** | **100%** |
|---|---|---|---|---|---|
| moves / hour | util% | util% | util% | util% | util% |
| 20 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 40 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 60 | 100.0 | 100.0 | 99.9 | 100.0 | 100.0 |
| 80 | 99.5 | 99.7 | 100.0 | 100.0 | 100.0 |
| 100 | 90.3 | 91.9 | 92.1 | 96.2 | 100.0 |
| 120 | 76.9 | 77.5 | 77.8 | 82.3 | 98.0 |

*Table 4 The effects of stacking pre-positioning for the circulation layout*

| **Production** | **0%** | **25%** | **50%** | **75%** | **100%** |
|---|---|---|---|---|---|
| moves / hour | util% | util% | util% | util% | util% |
| 20 | 98.0 | 99.8 | 100.0 | 100.0 | 100.0 |
| 40 | 99.9 | 100.0 | 100.0 | 100.0 | 100.0 |
| 60 | 99.8 | 99.8 | 99.9 | 100.0 | 100.0 |
| 80 | 99.9 | 99.9 | 100.0 | 100.0 | 100.0 |
| 100 | 97.1 | 99.1 | 99.5 | 99.5 | 99.8 |
| 120 | 87.7 | 94.3 | 96.5 | 97.7 | 98.0 |

*Table 5 The effects of stacking pre-positioning for the crossover layout*

When a high production is needed, pre-positioning of the containers in the stacklanes will improve the performance for both layouts. However, for the circulation layout, a pre-positioning close to 100% is needed for improvement. For the crossover layout, even a pre-positioning of only 25% leads to a significant improvement.

## CONCLUSIONS

Recognising that a transport capacity of about 70 moves per hour per quaycrane suffices, the results suggest that, purely concerning the quay transport, the crossover layout in combination with the proposed control system is capable to produce the desired service, also when slow AGVs are used. Also the circulation layout with fast AGVs may satisfy the requirements. The crossover layout requires a considerable smaller number of AGVs than the circulation layout. These results apply only when the performance of the QCs and the stacking cranes do not impose any restriction and when at least a quarter of the containers is stacked in favourable stack-lanes. Further research is required to study the performance in combination with other terminal operations. Crucial for the overall performance of the logistic chain at the terminal is the performance of the container stack.

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