OPTIMISING MACHINE USAGE FOR CONTAINER TRANSFERS AT MULTI-MODAL CONTAINER TERMINALS

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ABSTRACT
In a container terminal, containers unloaded from a ship are moved to the yard during the import operation. The export operation is the reverse of the import process. When a ship is served by multiple shore-cranes having both loading and unloading activities at the same time, a yard-machine can process an import container and an export container in one single round-trip. This paper investigates a model that concerns with the location and loading/unloading speed of shore-cranes, speed of yard machines, as well as the location of containers in the storage yard. The aim is to optimise the scheduling of container processes in maximising the efficiency of ports. The problem is solved using meta-heuristic techniques.

Key Words: Transportation, Scheduling, Optimisation

1. INTRODUCTION
Globalisation has brought with it an increase in the level of transportation. The world’s regions are also more closely linked with sources of raw material, manufacturing plants and markets worldwide (McCalla, 1999). World container traffic has already reached 236 million TEUs (twenty-foot equivalent units) in 2003 (UNCTAD, 2004).

Because of the economy of scales, larger and larger container vessels are being built. This leads to even higher capital investment for each new ship. With the high cost of vessels and of the goods they carry, shippers would obviously prefer a more reliable and efficient port of call. In a deregulated environment, keen competition exists between ports. To improve the port’s attractiveness, terminal operators are constantly under pressure to find ways to improve the reliability of their services, to reduce the overall transit times of container and to reduce costs as well.

Optimisation of container process with multiple shore-cranes is investigated in this study. The problem is formulated as a mixed integer programming problem (MIP), and solved by meta-heuristic techniques for obtaining optimal schedule in minimising the ship-time and the total travelling time of yard-machines.

1.1 Container Process
In Australia, shore-cranes are used in the main ports to load/unload containers to/from ships. During the import process, containers are first unloaded to the marshalling area, where yard machines (straddle-carriers, forklifts, etc) will pick the containers up and move them to the yard for temporary storage. These import containers will finally be moved further in-land by rail or by road. The export process is the reverse of the import process (see Figure 1).
The inside of a containership is constructed in the form of compartments. In each opening, the ship may hold one 40-foot or two 20-foot containers. Containers are stacked on top of the others in cells to a maximum of six levels high due to the limit in weight that the bottom container can withstand from those on top. Additional movable support is provided to the upper containers by the ship to achieve higher stacking capability. For this reason, extra time is needed for the handling of the movable support during loading and unloading activities. Besides, the time required to load/unload a container to/from a ship depends on the location of where it is stored on the ship as well as the speed of the shore-crane. Before a ship arrives, loading and unloading plans are developed, taking into account the number of shore-cranes assigned and the balance of the ship. From the plans, a database can be developed for the loading/unloading time for each container. This information is essential in analysing the container transfers at multimodal terminals.

A shore-crane can move along-side the berth. The marshalling area is where the shore-crane can pick-up/drop-off containers to/from the ship. Depending on the type of shore-crane in use, this area is normally six lanes wide. At each unloading position, import containers are unloaded to one of the lanes and stacking is to be avoided. Similarly, export containers are moved to one of the lanes before loading to the ship by the shore-crane during the export stage. At each loading/unloading position, the marshalling area forms a buffer.

When a shore-crane unloads more containers than the yard machines can handle, congestion occurs. The shore-crane must slow down or stop until space is available again. Similarly, yard machines must slow down or stop during the export stage if they operate faster than the shore-crane can handle.

### 1.2 Processing Time of Yard Machines

We consider the processing time of a yard-machine as the time in handling and transfer of an import/export container between the marshalling area and the storage yard. This processing
time depends on the speed of the machine, the unloading/loading position, its location at the storage yard and the starting position of the next container to be processed.

Figure 3. Forklift moving containers between marshalling area and storage yard

If a yard-machine is assigned an import container and then an export container, the yard-machine can complete the two tasks in one single round trip. The optimal schedule is not intuitive. Bigger ships can be 250 m in length or more. The separation between two unloading positions at the marshalling area can be quite significant, making it difficult to decide on whether a yard machine is to wait for the next container to be unloaded, or to pick up a container unloaded by another shore-crane. On the other hand, many ports are using yard machines of various types and models acquired at different years of operation. The fact that the equipment operates at different speeds further complicates the issue on finding an optimal schedule.

1.3 Literature Review

(Psaraftis, 1998) recommends research into a list of problems with the container terminal - scheduling berthing priorities; ship booking by “rendezvous”; berth and cranes allocation problem; yard management problem in minimising movements of straddle carriers; and route and schedule consolidation.

(Kozan, 2000) studies the flow of containers between various location (ships, berths, and different sections of storage yard) of a multimodal terminal, and the expected number handling due to the height of container stacks. This paper considers various types of handling and transfer equipment as well as the location of containers in the yard. A network model is proposed to minimize the total handling and travelling time of containers. (Kozan and Preston, 1999) develop a model to minimise the total travel and setup time of each yard machine in the storage area of a multimodal container terminal. When containers are stacked to multi levels or high, more handling time is needed to retrieve a container at the lower level of the stack. The problem is solved using Tabu Search. In a later study, (Preston and Kozan, 2001) develop the “container location model” for the optimal location of containers in the storage area of a multimodal terminal. The paper also investigates the storage policy, and the sensitivity of the number of yard machines assigned to a berth.

(Kim and Kim, 1999) study the routing of a single straddle-carrier in the storage yard. In the port investigated, a straddle-carrier enters a yard-bay to pick up a container. The container is then loaded to the yard trailer for transporting to the quay crane for loading. A model is proposed to minimise the distance travelled by the straddle-carriers between yard-bays. (Kim and Kim, 2001) estimate the cost of terminal operation. This paper also suggests a way to estimate the travel time of transfer crane between yard bays. The container "rehandling time"
is approximated using Gamma distribution. (Lai and Lam, 1994) paper applies queuing theory and simulation to study the throughput and utilisation of yard equipment under various allocation strategies. (Imai et al., 2001) propose a model for determining a dynamic berth assignment to ships in the public berth system. The objective is to minimise the total time of all ships in port within a planning horizon. The problem is solved using Lagrangian relaxation.

(Bish, 2003) investigates the case when import containers are loading to a ship and export containers are unloading to another ship at the same time. Combining the loading and unloading operations will save the total travel time of yard machines. The author proposes the “trans-shipment problem based list scheduling heuristic” for large size problems. (Vis and Koster, 2003) give a comprehensive review on the literature relating into recent research on container terminal. The authors suggest that future research needs to extend models for simple cases to a more “realistic situation”. An example is to extend the problem of routing a single straddle carrier during loading operations to the case of multiple straddle carriers during loading and unloading operations. Also they point out that more work needs to be done on the combination of various equipment. (Peterkofsky and Daganzo, 1990) formulate crane scheduling problem as machine scheduling problem, the crane scheduling problem becomes an “open shop” with parallel, identical machines processing jobs, and each job consisting of a number of independent single-stage, pre-emptable tasks.

The model establishes the nature of the relationship between significant factors and the options for increasing throughput by discovering the location of bottlenecks, which restrict entity flow through the system. There have been a number of attempts to solve various aspects of this overall problem. However as far as we know from the literature review and “Insider Knowledge” (ie. visits to various seaport container terminals, liaison with colleagues at seminars and conferences), little contemporary work has been done or publicised for large size container terminals. This confirms the present lack of research into integrated planning and control models and theory. To fill this gap, the following model is developed in this study for the effective use of container terminals’ infrastructure and associated functions.

2. A SIMULTANEOUS IMPORT-EXPORT PROCESS MODEL

Indices

Ship: \( s \in S \);
Shore-crane: \( c \in C_s \);
Yard-machines: \( m, m' \in M_s \)

Parameters

- \( B_s^i \) (\( B_s^e \)): Time required for ship \( s \) to berth (to leave from its berth position and to release the space for other ship)
- \( N_s^i, N_s^e \): Set of import (export) containers of ship \( s \in S \) unloaded from (loaded by) crane \( c \). Note that containers are arranged in the order of ship, shore-cranes and its loading/unloading sequence.
- \( N_s^i, N_s^e \): Set of import (export) containers of ship \( s \in S \)
- \( K_s \): Set of yard machine processing order of containers of ship \( s \)
- \( \tau_{s,j} \): Time required to load (unload) the import (export) container \( j \in N_s^i \) (\( j \in N_s^e \)) to (from) ship \( s \)
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Processing time of container \( j \) (\( j' \)) if yard machine \( m \) is to process container \( j \in N_s^i \) after finished \( j' \in N_s^o \)

\[ P_{s,m,j,j'}^1 \]

Travelling time yard machine \( m \) required between loading position of export container \( j' \in N_s^o \) and unloading position of import container \( j \in N_s^i \)

\[ \pi_{s,m,j,j'} \]

Scheduled time of arrival of ship \( s \)

\[ STA_s \]

Scheduled time of departure of ship \( s \)

\[ STD_s \]

Penalty on ship time

\[ w_s \]

Penalty on total processing time of yard machines

\[ w_s' \]

Variables

\[ t_{s,m,k}^1 \quad t_{s,m,k}^2 \]

Time when yard machine \( m \) starts (completes) in moving its \( k \)-th container between the yard and marshalling area

\[ R_{s,j} \]

Time when a shore crane starts unloading (loading) container \( j \) from (to) ship \( s \)

\[ ATA_s \]

Actual time of arrival

\[ ATD_s \]

Actual time of departure

\[ X_{s,m,j,k} \]

Binary variable represents whether the container \( j \) of ship \( s \) is the \( k \)-th container moved by yard machine \( m \)

\[ d_{s,j} \]

Processing time for container \( j \in (N_s^i \cup N_s^o) \)

\[ Z_s \]

Total processing time of yard machines of ship \( s \)

Assumptions

- The balance of ships are always maintained;
- Yard-machines work as a pool;
- Only one berth is involved;
- No delay of yard machines; and
- No storage buffer in marshalling area.

The Model

The objective is to minimise the weighted penalty on ship delay and the total processing time of yard machines:

\[ \text{Minimise} \quad \sum_s \left( w_s \times (ATD_s - ATA_s) + w_s' \times Z_s \right) \]  

To ensure ship \( s \) berths after its scheduled arrival and after the previous ship has departed:

\[ ATA_s \geq STA_s \]

\[ ATD_s' \geq ATD_{s-1} + B_{s-1}^o + B_s^i \]

Loading and unloading can not start until the ship berths:

\[ R_{s,j} \geq ATA_s + B_s^i \quad \text{for} \quad j \in (N_s^i \cup N_s^o) \]
Ship s leaves the berth after loading and unloading are complete on all holds:

\[ A T D_s = R_{s,j} + \tau_{s,j} + B^s_j \text{ for } j \in (N^i_s \cup N^e_s) \]  

(5)

Each container must be processed by a yard machine, and each yard machine can only process one container at a time:

\[ \sum_{m \in M} \left( \sum_{j \in (N^i_s \cup N^e_s)} X_{s,m,j,k} \right) = 1 \text{ for } j \in (N^i_s \cup N^e_s) \]  

(6)

\[ \sum_{j \in (N^i_s \cup N^e_s)} X_{s,m,j,k} \leq 1 \text{ for } j \in (N^i_s \cup N^e_s) \]  

(7)

Shore-crane loads and unloads containers one-by-one as planned:

\[ R_{s,j} \geq R_{s,j} + \tau_{s,j} \text{ for } j < j' \in (N^i_{s,c} \cup N^e_{s,c}) \]  

(8)

Yard machine cannot start processing any import container before the container is unloaded from ship

\[ t_{s,m,j}^1 \geq R_{s,j} + \tau_{s,j} - (1 - X_{s,m,j,k}) \times M \text{ for } j \in N^i_s \]  

(9)

Export containers can only be loaded to the ship after they are moved to the marshalling area:

\[ R_{s,j} \geq t_{s,m,k}^2 - (1 - X_{s,m,j,k}) \times M \text{ for } j \in N^e_s \]  

(10)

To ensure not more than one container at each loading/unloading position:

\[ R_{s,j} + \tau_{s,j} \geq t_{s,m,k}^1 - (1 - X_{s,m,j,k}) \times M \text{ for } j < j' \in N^i_{s,c} \]  

(11)

\[ t_{s,m,k}^2 \geq R_{s,j} - (1 - X_{s,m,j,k}) \times M - (1 - X_{s,m,j,k'}) \times M \]  

(12)

(13)

The start and end processing time of each container:

\[ t_{s,m,k}^1 \geq P_{s,m,j,k}^1 \text{ for } k \in K_s \]  

(14)

\[ t_{s,m,k}^2 \geq P_{s,m;j,k'}^2 \text{ for } k < k' \in K_s \]  

(15)

The processing time is sequence-dependent. When yard machine \( m \) processes an import container \( j \) followed by another import container \( j' \):

\[ t_{s,m,k}^2 \geq t_{s,m,k}^1 + P_{s,m,j,k'}^1 - (1 - X_{s,m,j,k}) M - (1 - X_{s,m,j,k'}) M \]  

(16)

Yard machine \( m \) processes export container \( j \) and then another export container \( j' \):

\[ t_{s,m,k}^2 \geq t_{s,m,k}^1 + P_{s,m,j,k'}^2 - (1 - X_{s,m,j,k}) M - (1 - X_{s,m,j,k'}) M \]  

(17)

Yard machine \( m \) processes import container \( j \) and then export container \( j' \):

\[ t_{s,m,k}^2 \geq t_{s,m,k}^1 + P_{s,m,j,k'}^1 - (1 - X_{s,m,j,k}) M - (1 - X_{s,m,j,k'}) M \]  

(18)

\[ t_{s,m,k}^2 \geq t_{s,m,k}^1 + P_{s,m,j,k'}^2 - (1 - X_{s,m,j,k}) M - (1 - X_{s,m,j,k'}) M \]  

(19)

When yard machine \( m \) processes an export container \( j \) and then an import container \( j' \), \( m \) may need to travel between shore-cranes:

\[ t_{s,m,k}^2 \geq t_{s,m,k}^1 + P_{s,m,j,k}^1 - (1 - X_{s,m,j,k}) M - (1 - X_{s,m,j,k'}) M \]  

(20)

Processing time for container:
\[ d_{s,j} \geq t^2_{s,m,k} - t^1_{s,m,k} - (1 - X_{s,m,j,k}) \beta M \quad \text{for } j \in (N'_K \cup N''_K); \ k \in K_s \]  
(21)

The total processing time of yard machines:
\[ Z_s = \sum_{j \in (N'_K \cup N''_K)} (d_{s,j}) \quad \text{(22)} \]

3. SOLUTION TECHNIQUES

The model proposed in this paper can be reduced to Parallel Machine Scheduling Problem \( P_m//C_{\text{max}} \). \( P_m//C_{\text{max}} \) is already known as NP-hard (see (Pinedo, 1995) and (Blazewicz, 1996)). With the large size of the real-life problem, optimal solution is almost impossible to find within a reasonable duration of time. For this reason, Tabu Search is used to solve the problem. Tabu Search is a meta-heuristic originally developed by Glover (see (Glover and Laguna, 1993)). This technique has been successfully applied to a variety of combinatorial problems by (Preston and Koizan, 2001).

Tabu Search for the optimal container process:

i. Initialise a feasible schedule for the container process.

ii. Calculate the objective value of the schedule.

iii. Store this schedule.

iv. Initialise an empty Tabu List.

v. Select a ship \( s \) and a yard machine \( m \) randomly. From machine schedule select a container \( j \) randomly.

vi. Find the best neighbourhood (see below).

vii. If there is improvement in objective value then

update the schedule with this new schedule

add \( j \) to the tabu list

else

if \( j \) is in the tabu list then

discard the new schedule

end if

end if

viii. Repeat from step v until stopping condition is met.

Starting from a schedule \( \mathcal{J} \) and randomly selected container \( j \) (to be processed by yard machine \( M1 \)), the best neighbourhood may be searched by one or more of the following operations (see Fig. 3a-d):

i. Select any other job \( j' \) of the same machine from \( \mathcal{J} \). Create a new schedule \( \mathcal{J}' \) by swapping \( j \) and \( j' \).

ii. Select any other job \( j' \) of the same machine from \( \mathcal{J} \). Create a new schedule \( \mathcal{J}' \) by inserting \( j' \) before \( j \), or by setting \( j' \) as the last job of \( M1 \).

iii. Select any job \( j' \) from any other machine \( M2 \) from \( \mathcal{J} \). Create a new schedule \( \mathcal{J}' \) by swapping \( j \) and \( j' \).

iv. Select any job \( j' \) from any other machine \( M2 \) from \( \mathcal{J} \). Create a new schedule \( \mathcal{J}' \) by inserting \( j' \) before \( j \), or by setting \( j' \) as the last job of \( M2 \).

From our trial experience, better performance was achieved using (3) and (4) together.

\[ \text{Figure 4a. Swapping jobs of same machine} \]
The system is implemented using C++. Table 1 shows the results averaged over 10 instances from a sample data set of 500 import and 500 export containers using a Pentium 4 2.8Hz HT system of 512M RAM. Initially, a feasible schedule is constructed by assigning same number of yard machines to each shore-crane. And according to their sequential order of loading/unloading, containers of a particular shore-crane are assigned to yard-machines in rotation. The stopping condition is defined as:

- the number of iterations exceed 100,000; or
- the standard deviation of the objective values averaged over 100 iterations is 2 minutes or above.

The objective function is the weight penalty on ship berthing time and total processing time of yard machines in the ratio of 90%:10%. The lower-bound of ship time calculated from the maximum sum of loading and unloading time for shore-cranes is also included in the table.

### Table 1. Experimental results from sample data

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<th>Number of Shore Cranes</th>
<th>Objective value</th>
<th>Ship time</th>
<th>Total processing time</th>
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<td></td>
<td>Initial</td>
<td>Best</td>
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30.5.8
The results show an improvement in ship time as well as the total processing time of yard machines.

4. CONCLUDING REMARKS

In this paper, a model for multi-crane simultaneous import and export is proposed. The problem in optimal schedule of container process for multiple shore-cranes is successfully solved using Tabu Search. Numerical results indicate an improvement in ship time as well as the total processing time of yard machines on our large-scale trial sample data set. We conclude that with the model developed here it is possible to increase the efficiency of sea-port terminals, and to minimise the fuel and maintenance cost of yard machines. Other meta-heuristics and the problem of dynamic location of multi-berth terminals are left to future works.

REFERENCES


