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<td>Author(s)</td>
<td>Guo, Xi; Huang, Shell Ying</td>
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Performing A* Search for Yard Crane Dispatching in Container Terminals

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Abstract

We address the problem of dispatching a yard crane in its appointed zone of a container terminal. The objective of yard crane dispatching is to determine a sequence for handling all coming jobs within the zone that minimizes the average vehicle waiting time. We propose 2 modified A* search algorithms with admissible heuristics to provide fast and optimal dispatching solution. Simulation results show that the algorithm using the improved heuristic is able to find the optimal solution over $2.4 \times 10^9$ possible dispatching sequences in about 3 to 4 seconds under heavy work load.

1. Introduction

When a vessel berths at a terminal, a number of Quay Cranes first unload containers from the vessel onto vehicles. Vehicles then travel to specific locations in the yard to be served by Yard Crane for temporary storage of containers in the yard. Then the loading of the vessel is carried out in the reverse order.

One way to organize the yard operations is to partition a yard into a number of non-overlapping zones to be handled by individual yard cranes in a planning window. Each zone may be part of one yard block, one yard block, or more than one yard blocks in the same row. Figure 1 shows a possible partition of the storage yard into zones in a typical container terminal.

In this paper we address the problem of dispatching a yard crane in its appointed zone to minimize vehicle waiting times and therefore to better support the continuous feeding of vehicles to the quay cranes and reduce vessel turnaround times. It is a complex problem with unique characteristics. The most important one is the each job’s waiting time and thus its finish time is affected by both the previous yard crane location and crane available time. This makes techniques like dynamic programming not quite applicable. An factor is an idle yard crane’s pre-gantry ability may shorten a vehicle waiting time. Unlike servers in job shop problems, the yard crane can not only be reactive to actual job arrivals but also proactive to near arrivals.

One difficulty of yard crane dispatching is the dynamics of job arrivals. Actual vehicle job arrivals hardly follow a fixed schedule. For example, a vehicle job could be delayed due to possible delay of a quay crane operation, a congestion encountered in vehicle travelling or human factors like individual driver behavior. This makes techniques like integer programming which requires job arrival information
completely known in advance not realistically feasible. However, with real-time tracking of terminal assets, it is possible to predict with high accuracy job arrivals in near future. We study the yard crane dispatching problem where the planning period is small such that job arrival information can be predicted accurately.

Even when the planning window is small, it is still too time consuming to find the optimal solution by conventional methods. The problem of yard crane dispatching has been proved to be NP-complete [3]. People have tried employing special machine like Integer Programming [2, 4] to explore all possibilities with smaller problem sizes than what we study here. Others proposed heuristic methods to reduce computation time by sacrificing optimism [5, 8], e.g. simulated annealing.

In this paper, we propose two algorithms which are guaranteed to find the optimal solution for a single crane in a planning window and are very fast to be used in real time environment. The proposed A* algorithms are admissible, complete and optimally effective [1].

The rest of the paper is structured as follows. Section 2 briefly reviews the related works. A formal problem description is given in Section 3. Our modified A* search algorithms for yard crane dispatching are presented in Section 4. Section 5 presents the experimental evaluation of the performance of our proposed algorithms. Conclusion is drawn in Section 6.

2. Related Work

Several focused studies on the yard crane dispatching problem in container terminals have been done. Kim and Kim [2] proposed a Mixed Integer Programming (MIP) method for the routing of a single yard crane to support the loading operations of a vessel. Based on the MIP formulation, an optimal algorithm is presented. Kim and Kim [5] presented heuristic algorithms for the same problem, which outperform a Genetic Algorithm (GA) shown by numerical experiments. However, the assumption in these works of having dedicated yard cranes just to support vessel loading operations is not always practical for terminals with many berths and more yard blocks than cranes. Ng [4] studied the problem of scheduling multiple yard cranes by modeling it as an integer program. A heuristic was proposed to minimize total loading time. However, loading sequence is not considered.

A* search has been widely adapted in various applications with domain specific heuristics. For examples, Hamdi and Mulvaney [6] proposed a Prioritized A* algorithm in solving real-time elevator dispatching problem; Lee and Cho [7] presented an application of the A* algorithm in manufacturing layout design. To the best of our knowledge, our work is the first to apply the A* technique to solve the yard crane dispatching problem in container terminals.

3. Problem Formulation

In this work, we make the following assumptions in the yard crane dispatching model:
- Each vehicle handles one container only.
- Future job information can be accurately predicted for a relatively short planning period, e.g., 2 hours.

The problem of dispatching a yard crane is stated as follows. There are $N$ jobs in the current planning period with (predicted) vehicle arrival times $A_i$ ($i = 1, 2, ..., N$) and their respective job slot locations. The yard crane service time of job $i$ is $S_i$, completion time of job $i$ is $F_i$ and the crane gantry time from job $x$ to job $y$ is $G_{xy}$. We represent the search space by a tree where each node is a job except the start node. An edge $(h, i)$ in the tree has a weight (cost) equal to the vehicle waiting time for job $i$ if the crane is to do job $i$ after finishing job $h$. This edge weight, $W_i$, is given by Equation (1):

$$W_i = F_i - S_i - A_i \quad (1)$$

The objective of minimizing average waiting time for vehicles is expressed as

$$\text{Min } \frac{1}{N} \sum_{i=1}^{N} (F_i - S_i - A_i)$$

When the arrival time and slot location of the next job is known beforehand, the yard crane could start moving towards the next job location in advance of the actual vehicle arrival. Job finishing time with this pre-gantry ability is shown in Equation (2):

$$F_{(i+1)} = \max \{A_{(i+1)}, F_i + G_{(i+1)} \} + S_{(i+1)} \quad (2)$$

[$i$] and [$i+1$] denote the $i$th and the ($i+1$)th jobs in the crane’s service sequence.

![Figure 3. Search Space of the Problem](image)

Search space of the tree representation of yard crane dispatching problem is shown in Figure 3. For a dispatching problem of $n$ jobs, each path from the start node to a leaf node in the tree represents a complete
dispatching sequence of height \( n \) and there are in total \( n! \) such paths. The objective of the problem is now transformed into finding the path which has minimum total cost from start to a leaf node.

4. Optimal Search Algorithms

We propose a modified A* search algorithm to find the optimal solution with 2 admissible heuristic functions to estimate the cost from a current node to a leaf node.

4.1 Modified A* search

Pseudocode of the Modified A* for yard crane dispatching is shown in Figure 4. In the calculation for the cost function of nodes, let

\[ N = \text{set of all jobs}, \ |N| = n \]

\[ P(x) = \text{set of jobs already in the (partial) path from the root of the tree to } x \]

\[ U(x) = N - P(x) \]

\( h(x) \) is the estimated lower bound cost of the path from node \( x \) to a leaf node. (3)

\[ g(x) = \sum W_i, \text{where } i \in P(x). \]

\[ f(x) = g(x) + h(x) \]

\[ f(x) = \text{determines the priority of node } x \]

\[ f(x) = \text{the cost from start to this node} \]

\[ f(x) = \text{Put node_start in the priority queue q_open} \]

\[ f(x) = \text{WHILE q_open is not empty} \]

\[ f(x) = \text{node_cur = remove_first (q_open)} \]

\[ f(x) = \text{IF } f(\text{node_cur}) \text{ is no better than } f(\text{node_best}) \]

\[ f(x) = \text{Return node_best} \]

\[ f(x) = \text{IF } \text{node_cur is a leaf node} \]

\[ f(x) = \text{Update node_best as node_cur} \]

\[ f(x) = \text{ELSE} \]

\[ f(x) = \text{Generate each node_successor of node_cur} \]

\[ f(x) = \text{FOR each node_successor x} \]

\[ f(x) = \text{Get true cost from start to this node } g(x) \]

\[ f(x) = \text{Estimate lower bound cost from this node } h(x) \]

\[ f(x) = \text{Get cost function } f(x) = g(x) + h(x) \]

\[ f(x) = \text{Add x node to priority queue q_open} \]

4.2 The First Admissible Heuristic \( h(x) \)

In this problem, an admissible heuristic means \( h(x) \) never overestimates the cost to handle the remaining jobs not in the path from root to \( x \). Now, the problem is how to evaluate \( h(x) \) where \( x \) is a successor node of \( \text{node_cur} \) in the algorithm presented in Figure 4. We illustrate this situation in Figure 5. All successors of \( \text{node_cur} \), that is, all jobs in \( U(\text{node_cur}) \), are to be put in a list \( L \) and re-indexed, where \( A_i \leq A_{i+1} \), for \( i = 1, 2, \ldots, M-1, M = |U(\text{node_cur})| \). Let

\[ L = \{J_i \mid i = 1, M \text{ and } A_i \leq A_{i+1} \} \]

Figure 5. Jobs in \( U(\text{node_cur}) \) re-indexed and generated as children of \( \text{node_cur} \).

Consider \( x = J_i \). To compute \( h(x) \), the cost from \( J_i \) to a leaf node, we need to estimate the total job waiting time for the remaining jobs, that is, jobs in \( U(x) \) where \( U(x) = U(\text{node_cur}) - \{J_i\} \). \( U(x) \) can be partitioned into two groups:

\[ U(x) = \{C_{\text{earlier}} \} + \{C_{\text{later}} \}, \text{ where } j = 1, 2, \ldots, i-1 \]

\[ C_{\text{earlier}} = \{J_j \}, \text{ where } j = i + 1, i + 2, \ldots, M \]

Jobs in \( C_{\text{earlier}} \) are the ones that arrive earlier than \( J_i \), therefore it is certain that these jobs have to wait for the service of \( J_i \) according to the current dispatching sequence. If we approximate the crane service time for all jobs by a constant value of \( T_s \), then it is for sure that the first job to be handled in \( C_{\text{earlier}} \) has to wait for at least \( T_s \). The second job to be handled in \( C_{\text{earlier}} \) will have to wait for at least two \( T_s \), the sum of the job service times of \( J_i \) and the first job handled in \( C_{\text{earlier}} \). Likewise, the last job to be handled in \( C_{\text{earlier}} \) will have to wait for at least \( (i-1) \) \( T_s \), the sum of the job service times for \( J_i \) and the previous \( (i-2) \) jobs in \( C_{\text{earlier}} \). If a job in \( C_{\text{later}} \) is to be served before a job in \( C_{\text{earlier}} \), its waiting time will be even longer. Thus, the minimum total waiting time for jobs in \( C_{\text{earlier}} \) due to the time the crane spent after the arrival of \( J_i \) on servicing other jobs is described in Expression (4).

\[ \sum_{j=1}^{i-1} (1 + 2 + \ldots + (i-1)) T_s = \sum_{j=1}^{i-1} jT_s \] (4)

In addition, for each job in \( C_{\text{earlier}} \), it definitely needs to wait for the time period from its arrival to the
arrival of \( J_i \) as \( J_i \) will be served first by the yard crane among all successors of node \( \text{node}_\text{cur} \). The minimum total waiting time for jobs in \( C_{\text{earlier}} \) till the arrival of \( J_i \) is

\[
(A_{i} - A_{i}) + ... + (A_{i} - A_{i-1}) = \sum_{j=1}^{i-1} (A_{i} - A_{j})
\]

The heuristic \( h(x = J_i) \) is then the sum of these two above components:

\[
h(i) = \sum_{j=1}^{i-1} jT_s + \sum_{j=1}^{i-1} (A_{i} - A_{j})
\]

Estimated minimum cost from node \( J_i \) to a leaf node is now labelled as \( h(i) \), where \( J_i \) is the ith job arrival among all the successors of node \( \text{node}_\text{cur} \). It is not difficult to prove that \( h(i) \) is admissible.

### 4.3 An Improved Heuristic \( h(x) \)

The closer a heuristic estimation \( h(x) \) is to the actual cost \( h^*(x) \), the better the performance of \( A^* \) search will be. The heuristic function presented in the last section estimates the job waiting times for those jobs which arrive earlier than \( x = J_i \). We could improve the heuristic further.

\[
\sum_{j=1}^{i-1} jT_s + \sum_{j=1}^{i-1} (A_{i} - A_{j})
\]

The improved heuristic combines this component and the previous two as follows.

\[
h(i) = \sum_{j=1}^{i-1} jT_s + \sum_{j=1}^{i-1} (A_{i} - A_{j}) + \sum_{j=1}^{i} \text{Max} \{0, F_i - A_{j}\}
\]

The heuristic function is expected to provide better estimates of the actual costs \( h^*(x) \) which will reduce further the computational time for the optimal dispatching sequence. It is still admissible as the third component added can never overestimate the cost contributed by the jobs in \( C_{\text{later}} \).

### 5. Performance Evaluation

#### 5.1 Experimental Design

To evaluate the performance of the proposed yard crane dispatching algorithms, simulation experiments were carried out. Parameter settings were obtained from real world terminal models. Each experiment computes 20 jobs corresponding to a planning period of 1 to 3 hours depending on job inter-arrival times. Intra-block speed of the crane is 7.8km/hour. Inter-block gantry between two adjacent blocks of the same row takes 200 seconds and the yard crane service time is taken as a constant of 180 seconds for all jobs. Two sets of experiments were conducted with zones of sizes of 1 and 2 yard blocks respectively. Three scenarios of different vehicle arriving rates were tested. The means of the exponential distributions of inter-arrival times are listed in Table 1 in unit of seconds. Heavy load means a job arrival rate slightly smaller than the yard crane’s servicing rate (crane service time + average inter job gantry time). The slot locations of the jobs are generated randomly within the zone.

Four algorithms evaluated are: \( A^* \) with the first heuristic (H1), \( A^* \) with improved heuristic (H2), pure greedy search and exhaustive search. Pure greedy is a search algorithm by expanding the node whose current cumulated waiting time is minimum using \( f(x) = g(x) \). Exhaustive search is implemented by depth first search. As the problem tree is finite and all branches have same depth, the search is complete and optimal. For each setting, 15 independent runs were performed and results are the averages from these multiple runs.

#### 5.2 Results Analysis

<table>
<thead>
<tr>
<th>Zone</th>
<th>Heavy Load</th>
<th>Normal Load</th>
<th>Light Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone = 1 BLK</td>
<td>240s</td>
<td>300s</td>
<td>420s</td>
</tr>
<tr>
<td>Zone = 2 BLKs</td>
<td>390s</td>
<td>480s</td>
<td>570s</td>
</tr>
</tbody>
</table>
The quality of a yard crane dispatching algorithm is measured by two indicators: the time to compute the dispatching plan and the quality of the dispatching plan. For all algorithms used in the experiments, we are looking for the optimal dispatching solution with minimum average job waiting time.

Data in Table 2 show that the A* algorithm with heuristic H2 takes less computational time to find the optimal solution than H1 when the zone size is 1 block under all three work load cases. It means H2 expands fewer nodes than H1 for the same problems. This suggests that the heuristic used in H2 is able to generate an estimation of the total waiting time closer to the actual total waiting time than H1. These results show that A* search can produce optimal crane dispatching sequence with very low computational costs. Even in the heavy load case, H2 can find the optimal solution out of over $2.4 \times 10^8$ possible dispatching sequences in about 3 seconds. This is good enough even to be used in real time environment.

### Table 2. Computational Time of Zone = 1BLK/2BLKs

<table>
<thead>
<tr>
<th>Load</th>
<th>H1</th>
<th>H2</th>
<th>Pure Greedy</th>
<th>Exhaustive Search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Load</td>
<td>6.36/4.72</td>
<td>3.12/2.72</td>
<td>Run Out of Memory</td>
<td>Run Out of Time (&gt;7200 sec)</td>
</tr>
<tr>
<td>Normal Load</td>
<td>2.54/3.30</td>
<td>1.30/1.07</td>
<td>Run Out of Memory</td>
<td>Run Out of Time (&gt;7200 sec)</td>
</tr>
<tr>
<td>Light Load</td>
<td>0.47/0.77</td>
<td>0.31/0.54</td>
<td>Run Out of Memory</td>
<td>Run Out of Time (&gt;7200 sec)</td>
</tr>
<tr>
<td>1BLK/2BLKs</td>
<td>A*</td>
<td>A*</td>
<td>Pure Greedy</td>
<td>Exhaustive Search</td>
</tr>
</tbody>
</table>

Pure greedy search run out of memory in all cases tested. It is because the algorithm keeps too many partially evaluated crane dispatching sequences in the memory when employing the heuristic $h(x) = g(x)$. This shows that $g(x)$, the current accumulated waiting time from the partial dispatching sequence, is a very poor estimation to the actual cost $h(x)$. When a search algorithm cannot get the optimal results within two hours we interpret it as running out of time, because such amount of time is not acceptable in real time operational management. Experiments show that in all cases tested exhaustive search would run out of time.

When the work load of vehicle job arrivals is heavy, Modified A* search algorithms of both H1 and H2 need to take more time to work out the optimal solution. This can be explained using queuing theory: the closer job arrival rate to the service rate (yard crane handling rate) is, the higher probability is to see queuing jobs. When several vehicle jobs wait for the yard crane service, their relative job locations would be an important factor in determining the optimal service order. The algorithms need to expand and evaluate more partial job sequences in finding the optimal, resulting in longer computational times.

Similar results have been obtained in the zone with 2 blocks. Comparing results across two zone sizes, we find H2 always performs better than H1 under different work load cases. We could conclude that H2 is more effective than H1. A* search with Heuristic H2 is fast enough to be used in real time environments to find the optimal solution.

### 6. Conclusion

In this paper, we address the problem of yard crane dispatching in container terminals. Modified A* search algorithms with 2 admissible heuristics are proposed to compute optimal dispatching solutions. Experiments were carried out to evaluate the algorithms under three various work load cases in two yard zones of different sizes: 1BLK and 2BLKs. Results show that the proposed algorithms consistently perform very well over all tested cases. Our modified A* search with the improved heuristic is able to find the optimal solution over $2.4 \times 10^8$ possible dispatching sequences in about 3 to 4 seconds under heavy work load. This actually suggest that in the situation where if there is some update/change in job arrival information in real time, the dispatching sequence may be re-computed without delaying the crane operations.

### 7. References