INTEGRATED SCHEDULING OF SP-AS/RS AND HANDLING EQUIPMENT IN AUTOMATED CONTAINER TERMINALS

S.M. Homayouni1,*, M.R. Vasili1, S.M. Kazemi1, S.H. Tang2
1Department of Industrial Engineering
Lenjan Branch, Islamic Azad University, Isfahan, Iran
homayouni@iauln.ac.ir
kazemi@iauln.ac.ir
vasili@iauln.ac.ir

2Mechanical and Manufacturing Engineering Department,
Engineering Faculty, Universiti Putra Malaysia, Selangor, Malaysia
saihong@eng.upm.edu.my

ABSTRACT
Conventionally, the containers are stacked in storage yards inside the container terminals. However, in recent years a new storage system called split-platform automated storage/retrieval system (SP-AS/RS) has been introduced in the literature. On the other hand, integrated scheduling of handling equipment has been introduced as an essential concept to improve the performance of the automated container terminals. Improving the performance of container terminals would result in reduction of seaborne trade costs. In this paper a mixed integer programming model is formulated for the integrated scheduling of handling equipment (including the SP-AS/RS) in automated container terminals. In the formulation of the problem, tasks of cranes are scheduled considering the availability of the vehicles. Moreover, the vehicles are scheduled in accordance with the SP-AS/RS operations. The integrated scheduling has been proved as an NP-hard problem. Thus, a simulated annealing algorithm is developed to find near optimal solutions for the problem in relatively low computational time. Using a set of numerical test cases it is justified that the proposed simulated annealing algorithm is suitable to solve the problem. Further analyses on the number of available vehicles are the final notes of this paper.

* Corresponding Author
1 INTRODUCTION

The goal of the seaport container terminals is to move the containers as quickly as possible and at the least possible cost [1]. In most of the container terminals, a large portion of the terminal turnaround time is spent on unloading and loading containers of a vessel [2]. Therefore, it is essential for a container terminal to efficiently and rapidly receive, store, and dispatch containers [3]. An efficient port must ensure that ships are unloaded and loaded quickly [4]. Since containers are large and heavy, specialized material handling systems are required for transporting them within the terminal. Some examples of equipment are quay cranes, vehicles, and straddle carriers.

Automated container terminals (ACTs) are an integration of cranes, vehicles, and storage yards, controlled unmanned. Automated guided vehicles (AGVs) [5] and automated lifting vehicles [6] have been introduced in the literature to transfer the containers between quayside and storage yard within ACTs. For the storage yards, automated stacking cranes have been used widely in practice. However, a split-platform automated storage/retrieval system (SP-AS/RS), with the principle of separating horizontal and vertical transport to cater for the weight and size constraints and to achieve better operating flexibility, has been introduced by Hu et al. [7]. Hu et al. [7] and Vasili et al. [8] developed the expected travel time models for various design of SP-AS/RS and proposed the best shape and dwell point policy in the SP-AS/RS.

This paper presents a new formulation for the integrated scheduling of handling equipment including the SP-AS/RS in ACTs. Following sections are organized to pursue the aim of the research. Section two reviews the most important literature related to the problem. The integrated scheduling of quay cranes (QCs), the SP-AS/RS, and AGVs is described briefly in section three. The formulation of the integrated problem is presented in this section, too. Section four presents the fundamental notes for the proposed simulated annealing algorithm (SAA). The numerical test and evaluation of the proposed scheduling methods is reported in section five. Finally, the concluding remarks of the paper are presented in section six.

2 LITERATURE REVIEW

Lau and Zhao [9] demonstrated that the main loss of performance at ACTs is the uncoordinated scheduling of its various handling equipment. Bierwirth and Meisel [10] reviewed past literature on the integrated QC scheduling and berth allocation planning. Lee et al. [11] proposed an integrated method to schedule yard trucks and storage allocation problems in container terminals. Nguyen and Kim [6] formulated the integrated scheduling of automated lifting vehicles and the QCs in container terminals. They proposed a heuristic algorithm to overcome excessive computational time of mathematical model. Homayouni et al. [12] proposed a mathematical model and a simulated annealing algorithm to solve the integrated scheduling problem of AGVs and QCs in container terminals.

Meersmans and Wagelmans [13] seem to be the first researchers to consider integrated scheduling of three handling equipment. They presented a branch-and-bound algorithm and a beam search heuristic algorithm for the integrated scheduling of QCs, AGVs, and stacking cranes in ACTs. They focused on minimization of the makespan of all operations in the ACT. Chen et al. [14] proposed a tabu search method for the integrated scheduling of QCs, yard vehicles, and yard cranes, in container terminals. The objective function of their research is to minimize the makespan. Lau and Zhao [9] proposed a mixed integer-programming model for the integrated scheduling of QCs, AGVs, and automated yard cranes, aiming for minimization of both makespan and delay time in operations of ACTs. Liang et al. [15] proposed a mixed integer-programming model for the integrated scheduling of QCs, inner trucks and yard cranes. They proposed a heuristic method to solve the problem.

Many of the researchers have implemented the simulated annealing algorithm to optimize problems in container terminals. Kim and Moon [16] proposed a simple SAA to optimize the berth allocation problem. Moorthy and Teo [17] solved the same problem by using the SAA.
Furthermore, Lee et al. [18] have developed an SAA to minimize the average handling time in container terminals. They scheduled two yard cranes serve one QC; and found the best combination of the control parameters for this problem. Later, Vis and Carlo [19] have optimized the scheduling of two automated stacking cranes in a stacking bay. They proposed an SAA to minimize the makespan of both automated stacking cranes. Moreover, Legato et al. [20] used an SAA to solve the vessel loading/unloading problem in ACTs.

3 PROBLEM DEFINITION AND FORMULATION

There are two kinds of tasks in vessel operations, i.e. loading and unloading the containers. In agreement to Lau and Zhao [9], in this paper, it is supposed that loading and unloading tasks are handled by the equipment concurrently. The automated container terminal in this paper comprise of some QCs, a fleet of AGVs, and some racks of SP-AS/RS. Figure 1 illustrates the structure of one storage rack in the SP-AS/RS proposed by Hu et al. [7], where two vertical platforms (VP), and some horizontal platforms (HP) transfer the container to the storage cells.

In loading tasks, a container should be collected from the storage cell in the SP-AS/RS, and be delivered to the QCs by using the AGVs. The container stored in a storage cell is picked up by the dedicated HP which transfers it to the handover station (H/O) where the container is delivered to the dedicated VP. Once VP receives the container, it moves to the load/unload station (L/U), where the container is delivered to the AGV. The AGV receives the container and moves it to the desired QC. The QC picks up the container and loads it to the predefined location in the vessel. Operational time (OQ) and travelling time (TQ) of the QCs are supposed to be deterministic. The dwell point policy for all the equipment is “stay at place”. Thus, in loading tasks, dwell point for HPs, VPs, AGVs, and QCs are at H/O, L/U, dedicated QC, and on top of the vessel, respectively. Obviously, the equipment is not ready to pass to the next task unless it delivers the container to next appointed equipment. Therefore, the HPs may block the VP, and vice versa; or the AGV may be blocked by the SP-AS/RS due to delays in the assigned tasks. The operations in unloading tasks are in opposite direction of the loading tasks and the container is unloaded from the vessel and stored in the SP-AS/RS.

For any of the equipment in loading or unloading tasks, there might be two journeys. First to travel from its dwell point to the starting point of a task, and the second is to travel from starting point of the task to its final destination. The $i^{th}$ task of QC$_k$ is denoted by $T_{ki}$. If $T_{ki}$ and $T_{lj}$ are performed successively, by using the same AGV, $T_{a_{ki}}^{lj}$ is defined as the time required for the AGV to start its journey from its dwell point in $T_{ki}$ to the starting point of $T_{lj}$, and $T_{b_{ki}}^{lj}$ is defined as the time required for the AGV to move from the starting point of $T_{lj}$ to its final destination. On the other hand, $O_{mn}$ illustrates $n^{th}$ operation on storage rack number $m$ ($S_m$). If $O_{mn}$ and $O_{mp}$ are two tasks which are executed consecutively by the same
VP or the same HP, \(TV_{\text{m} \text{n}}\) and \(TH_{\text{m} \text{n}}\) is defined as travel time by the VP and HP from their dwell point in \(O_{\text{mn}}\) to the starting point of \(O_{\text{mp}}\), respectively. Similarly, travel time from the starting point of \(O_{\text{mp}}\) to its final destination is represented as \(TV_{\text{b} \text{m} \text{n}}\) and \(TH_{\text{b} \text{m} \text{n}}\), respectively. Travel time of the AGVs, HPs, and VPs are dependent on the type of tasks. Table 1 illustrates the travel time for AGVs, HPs, and VPs. Additionally, \(ES_{\text{ki}}\) is defined as the earliest possible completion time for \(QC_k\) on \(T_{\text{ki}}\).

| Table 1: Illustration For Travelling Time Of AGVs, VPs and HPs |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(T_{\text{ki}}/O_{\text{mn}}\) | \(T_{\text{ij}}/O_{\text{mp}}\) | \(T_{\text{fa}}^{ij}_{\text{kl}}\) | \(T_{\text{fb}}^{ij}_{\text{kl}}\) | \(TH_{\text{a} \text{m} \text{n}}\) | \(TH_{\text{b} \text{m} \text{n}}\) | \(TV_{\text{a} \text{m} \text{n}}\) | \(TV_{\text{b} \text{m} \text{n}}\) |
| L | L | QC\(_k\) \(\rightarrow\) SR\(_ij\) | SR\(_ij\) \(\rightarrow\) QC\(_l\) | H/O \(\rightarrow\) C\(_m\) | C\(_m\) \(\rightarrow\) H/O | L/U \(\rightarrow\) R\(_mp\) | R\(_mp\) \(\rightarrow\) L/U |
| L | U | QC\(_k\) \(\rightarrow\) QC\(_l\) | QC\(_l\) \(\rightarrow\) SR\(_ij\) | H/O \(\rightarrow\) H/O | H/O \(\rightarrow\) C\(_m\) | L/U \(\rightarrow\) L/U | L/U \(\rightarrow\) R\(_mp\) |
| U | L | SR\(_ij\) \(\rightarrow\) SR\(_ij\) | SR\(_ij\) \(\rightarrow\) QC\(_l\) | C\(_m\) \(\rightarrow\) C\(_m\) | C\(_m\) \(\rightarrow\) H/O | R\(_mp\) \(\rightarrow\) R\(_mp\) | R\(_mp\) \(\rightarrow\) L/U |
| U | U | SR\(_ij\) \(\rightarrow\) QC\(_l\) | QC\(_l\) \(\rightarrow\) SR\(_ij\) | C\(_m\) \(\rightarrow\) H/O | H/O \(\rightarrow\) C\(_m\) | R\(_mp\) \(\rightarrow\) L/U | L/U \(\rightarrow\) R\(_mp\) |

To develop the mixed integer programming (MIP) model for the prescribed scenario of the loading/ unloading task, the set of loading and unloading tasks are denoted by \(L\) and \(U\), respectively. Moreover, set of QCs, storage racks, and AGVs are denoted by \(K\), \(M\), and \(A\), singly. It is assumed that the AGVs are located at L/U stations in their initial events and will return to the initial position upon the completion of their assigned tasks. Moreover, HPs and VPs are in the first cell of the rows as their initial position and will return there once they complete the assigned operations. Thus, \(S\) and \(V\) are the set of initial position of the AGVs and VPs, and their initial event is represented by \(T_{\text{SI}}\) and \(O_{\text{mn}}\), respectively. Besides, \(F\) and \(W\) are the set of final position of AGVs, VPs, and their final event is denoted by \(T_{\text{FI}}\) and \(O_{\text{mn}}\), correspondingly. The initial and final positions of HPs are denoted by \(H\), and their initial and final operations are symbolized by \(O_{\text{mn}}\).

\(QC_k\) is the QC number \(k\) in quayside and the number of its predetermined tasks is represented by \(Q_k\). \(S_m\) is the storage rack number \(m\) in the storage area, and \(R_m\) is the set of rows in the \(S_m\). Moreover, \(N_m\) is the number of tasks predefined for the \(S_m\), in the storage rack, \(C_m\) is the storage cell to \(O_{\text{mn}}\) which is located in \(R_m\). Moreover, \(X_{\text{km}n}=1\), if \(O_{\text{mn}}\) and \(T_{\text{kl}}\) are related to one task, and 0 otherwise.

Decision variables of the proposed MIP model can be defined as follows. \(\alpha_{\text{kl}ij}^U_{\text{kl}}=1\), if \(T_{\text{ij}}\) is performed by the same AGV after \(T_{\text{kl}}\) and 0 otherwise. \(\alpha_{\text{m}n}^U=1\), if \(O_{\text{mp}}\) is performed after \(O_{\text{mn}}\) by the same AGV on \(S_m\) and 0 otherwise. \(\psi_{\text{mp}}=1\), if \(O_{\text{mp}}\) is performed after \(O_{\text{mn}}\) by the same HP on \(S_m\) and 0 otherwise. \(TQC_k\) denotes the completion time of the operations of \(QC_k\) on \(T_{\text{ki}}\), and \(TLU_{\text{ki}}\) is defined as completion time of operations of \(L/U\) on \(T_{\text{ki}}\). \(TH_{\text{mn}}\) is the time that HP finishes its initial operations on \(O_{\text{mn}}\), and \(TH_{\text{m}n}\) is the completion time of HP operations on \(O_{\text{mn}}\). Moreover, \(TM_{\text{mn}}\) is the time that VP finishes its initial operations on \(O_{\text{mn}}\), and \(TV_{\text{m}n}\) is the completion time of VP operations on \(O_{\text{mn}}\). The proposed MIP model for the integrated scheduling of handling equipment including the SP-AS/RS is presented in equations 1 to 21.

\[
\begin{align*}
\text{Min Z: } & \alpha \left( \sum_{k=1}^{K} \sum_{i=1}^{W} \sum_{j=1}^{U} \sum_{l=1}^{S} \sum_{n=1}^{N} \sum_{m=1}^{M} \alpha_{\text{kl}ij}^U_{\text{kl}} \right) T_{\text{a}m} + \sum_{k=1}^{K} \left( TQC_k \psi_{\text{m}n} - ES_{\text{m}n} \right) + \gamma \left( \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{p=1}^{\left(S_m \vee W\right)} \sum_{q=1}^{Q} \left( T_{\text{vb}m} \psi_{\text{m}n} \right) + \sum_{k=1}^{K} \sum_{i=1}^{W} \sum_{j=1}^{U} \sum_{k=1}^{K} \sum_{i=1}^{W} \sum_{j=1}^{U} \sum_{l=1}^{S} \sum_{n=1}^{N} \sum_{m=1}^{M} \left( T_{\text{vb}m} \psi_{\text{m}n} \right) \right) \\
& + \gamma \left( \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{p=1}^{\left(S_m \vee H\right)} \sum_{q=1}^{Q} \left( T_{\text{vb}m} \psi_{\text{m}n} \right) + \sum_{k=1}^{K} \sum_{i=1}^{W} \sum_{j=1}^{U} \sum_{k=1}^{K} \sum_{i=1}^{W} \sum_{j=1}^{U} \sum_{l=1}^{S} \sum_{n=1}^{N} \sum_{m=1}^{M} \left( T_{\text{vb}m} \psi_{\text{m}n} \right) \right) \right)
\end{align*}
\]

Subject to:

\[
\sum_{i=1}^{W} \sum_{j=1}^{U} \alpha_{\text{kl}ij}^U_{\text{kl}} = 1 \quad \text{for } \forall k \in K \cup S; \quad i = 1, \ldots, Q_k
\]
\[
\sum_{k=1}^{K_S} \sum_{i=1}^{Q_k} \Omega_{ki}^{ij} = 1 \quad \text{for } \forall l \in K \cup F; \ j = 1, \ldots, Q_l \quad (3)
\]

\[
\sum_{n=1}^{N_{m \cup \{V, W\}}} \Theta_{mn}^{mp} = 1 \quad \text{for } \forall m \in M; p = 1, \ldots, N_m \cup \{V, W\}; \text{ if } p \neq n \quad (4)
\]

\[
\sum_{p=1}^{N_m} \Theta_{mp}^{mn} = 1 \quad \text{for } \forall m \in M; n = 1, \ldots, N_m \cup \{V, W\}; \text{ if } p \neq n \quad (5)
\]

\[
\sum_{n=1}^{N_m} \Psi_{mn}^{mp} = 1 \quad \text{for } \forall m \in M; p = 1, \ldots, N_m \cup \{V, W\}; \text{ if } R_{mn} = R_{mp} \text{ and } p \neq n \quad (6)
\]

\[
\sum_{p=1}^{N_m} \Psi_{mn}^{mp} = 1 \quad \text{for } \forall m \in M; n = 1, \ldots, N_m \cup \{V, W\}; \text{ if } R_{mn} = R_{mp} \text{ and } p \neq n \quad (7)
\]

\[
T_m V_m^p - A \geq B M (\Theta_{mn}^{mp} - 1)
\]

\[
\text{for } \forall m \in M; n = 1, \ldots, N_m \cup \{V, W\}; p = 1, \ldots, N_m \cup \{V, W\}; \text{ if } O_{mp} \in L \quad (8)
\]

\[
T V_p^m - B \geq B M (\Omega_{mn}^{mp} + \Omega_{ki}^{ij} - 2)
\]

\[
\text{for } \forall m \in M; n = 1, \ldots, N_m \cup \{V, W\}; p = 1, \ldots, N_m \cup \{V, W\};
\]

\[
\forall k \in K; i = 1, \ldots, Q_k; j = 1, \ldots, Q_l; \text{ if } X_{ij}^{mp} = 1 \text{ and } O_{mp} \in L \quad (9)
\]

\[
T_m V_m^p - A \geq B M (\Psi_{mn}^{mp} + \Theta_{mn}^{mp} - 2)
\]

\[
\text{for } \forall m \in M; n = 1, \ldots, N_m \cup \{V, W\}; p = 1, \ldots, N_m \cup \{V, W\};
\]

\[
\forall k \in K; i = 1, \ldots, Q_k; j = 1, \ldots, Q_l; \text{ if } X_{ij}^{mp} = 1 \text{ and } O_{mp} \in U \quad (10)
\]

\[
T V_p^m - B \geq B M (\Omega_{mn}^{mp} - 1)
\]

\[
\text{for } \forall m \in M; n = 1, \ldots, N_m \cup \{V, W\}; p = 1, \ldots, N_m \cup \{V, W\}; \text{ if } O_{mp} \in U \quad (11)
\]

\[
T m H_{mp} - C \geq B M (\Psi_{mn}^{mp} - 1)
\]

\[
\text{for } \forall m \in M; n = 1, \ldots, N_m \cup H; p = 1, \ldots, N_m \cup H_r \quad (12)
\]

\[
T H_{mp} - D \geq B M (\Psi_{mn}^{mp} - 1)
\]

\[
\text{for } \forall m \in M; n = 1, \ldots, N_m \cup H; p = 1, \ldots, N_m \cup H_r \quad (13)
\]

\[
T L U_{ki} = T V_p^{mn}
\]

\[
\text{for } \forall k \in K; i = 1, \ldots, Q_k; m \in M; n = 1, \ldots, N_m; \text{ if } X_{ki}^{mp} = 1 \& T_{ki} \in L \quad (14)
\]

\[
T L U_{ki} - (T m V_m^p - T V b_{mn}^{mp}) \geq B M (\Omega_{mn}^{mp} - 1)
\]

\[
\text{for } \forall k \in K; i = 1, \ldots, Q_k; m \in M; n = 1, \ldots, N_m; p = 1, \ldots, N_m; \text{ if } X_{ki}^{mp} = 1 \& T_{ki} \in U \quad (15)
\]

\[
T Q C_{ij} - E \geq B M (\Omega_{ki}^{ij} - 1)
\]

\[
\text{for } \forall k \in K \cup S; l \in K \cup F; i = 1, \ldots, Q_k; j = 1, \ldots, Q_l \quad (16)
\]

\[
T Q C_{ki} \geq E S_{ki}
\]

\[
\text{for } \forall k \in K; i = 1, \ldots, Q_k \quad (17)
\]

\[
T Q C_{ki} - T Q C_{k(i-1)} \geq E S_{ki} - E S_{k(i-1)}
\]

\[
\text{for } \forall k \in K; i = 2, \ldots, Q_k \quad (18)
\]

\[
\Omega_{ki}^{ij} = 0 \text{ or } 1 \quad \text{for } \forall k \in K \cup S; \forall l \in K \cup F; i = 1, \ldots, Q_k; j = 1, \ldots, Q_l \quad (19)
\]

\[
\Theta_{mn}^{mp} = 0 \text{ or } 1 \quad \text{for } \forall m \in M; n = 1, \ldots, N_m \cup \{V, W\}; p = 1, \ldots, N_m \cup \{V, W\} \quad (20)
\]

\[
\Psi_{mn}^{mp} = 0 \text{ or } 1 \quad \text{for } \forall m \in M; n = 1, \ldots, N_m \cup H; p = 1, \ldots, N_m \cup H_r \quad (21)
\]

The objective function (1) minimizes total travel time of AGVs, HPs and VPs (loaded or empty) in addition to total delays in QC completion times. \(a, B, \) and \(y\) are constants to represent the cost of various objectives of the model. Lau and Zhao [9] proposed 0.1, 0.8, and 0.1 for \(a, B, \) and \(y\), respectively. Constraint sets (2) and (3) imply that the tasks for the QCs should be preceded or followed by only one task using the same AGV. The same constraints for HPs and VPs are stated in constraints (4) to (7). Therefore, for any of the handling equipment involved in scheduling problem, a chain of operations is scheduled.

The second set of constraints (8 to 18) calculates the exact completion time for the assigned tasks to the handling equipment. \(BM\) in these constraints is a relatively large positive number. Constraints (8) and (9) calculate the completion time for the first and second journeys of the VPs in loading tasks. Similarly, constraints (10) and (11) calculate the
completion time for the journeys of VPs in unloading tasks. Details of these constraints are presented in Table 2. Constraints (12) and (13) calculate the completion time for the operations of HPs in \( O_{mp} \). Details for these constraints are reported in Table 3. Constraints (14) and (15) calculate the time that AGV is able to deliver (receive) the container to (from) the L/U station in loading (unloading) tasks. Constraint (16) calculates the completion time of QC operation in \( T_lj \). The calculation for this constraint is different for various possible set of characteristics of tasks \( T_{ki} \), \( T_{lj} \) and \( T_{lj-1} \) that are illustrated in Table 4. Furthermore, constraint (17) states that completion time of \( T_{ki} \) should be greater than its earliest possible completion time; and constraint (18) implies that the completion time of subsequent task in a QC should be greater than its prior task by at least the differences of their earliest possible completion time. Finally, equations 19 to 21 emphasized that all the decision variables \( \Omega_{ki} \), \( \Theta_{mn} \), and \( \Psi_{mn} \) are binary variables.

Table 2: Calculations For Constraints (8 to 11)

<table>
<thead>
<tr>
<th>( O_{mn} )</th>
<th>( O_{mp} )</th>
<th>( T_{ki} )</th>
<th>A for (( TmV_{mp} ))</th>
<th>B for (( TVP_{mp} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>L or U</td>
<td>L or U</td>
<td>L or U</td>
<td>( TVP_{mn} + TVa_{mn} )</td>
<td>( Max ({THP_{mp} + TVb_{mn} }, {TQC_{ki} - TQ - OQ + T_{a_{ki}^{ij}}}))</td>
</tr>
<tr>
<td>L or U</td>
<td>U</td>
<td>L or U</td>
<td>( TVP_{mn} + TVa_{mn} )</td>
<td>( Max ({THP_{mp} + TVb_{mn} }, {TLU_{ki} + T_{a_{ki}^{ij}}}))</td>
</tr>
<tr>
<td>L or U</td>
<td>L or U</td>
<td>U</td>
<td>( Max ({TVP_{mn} + TVa_{mn,1} }, {TQC_{0j} + T_{b_{ki}^{ij}}}) + TVb_{mn} )</td>
<td>( Max (TmH_{mp}, TmV_{mp}))</td>
</tr>
</tbody>
</table>

Table 3: Calculations for Constraints (12 and 13)

<table>
<thead>
<tr>
<th>( O_{mp} )</th>
<th>C for (( TmH_{mp} ))</th>
<th>D for (( THP_{mp} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>( THP_{mn} + THa_{mn} + THb_{mn} )</td>
<td>( Max (TmH_{mp}, TmV_{mp}))</td>
</tr>
<tr>
<td>U</td>
<td>( THP_{mn} + THa_{mn} + THb_{mn} )</td>
<td>( Max (TmH_{mp}, TmV_{mp}) + THb_{mn} )</td>
</tr>
</tbody>
</table>

Table 4: Details of Calculations For Constraint (16)

<table>
<thead>
<tr>
<th>( T_{ij} )</th>
<th>( T_{lj(i-1)} )</th>
<th>( T_{ki} )</th>
<th>( E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>L or U</td>
<td>L or U</td>
<td>( Max (TQC_{0j-1} + TQ, TLU_{ij} + T_{b_{ki}^{ij}}) + TQ + OQ)</td>
</tr>
<tr>
<td>L</td>
<td>U</td>
<td>L or U</td>
<td>( Max (TQC_{0j-1}, TLU_{ij} + T_{b_{ki}^{ij}}) + TQ + OQ)</td>
</tr>
<tr>
<td>U</td>
<td>U</td>
<td>U</td>
<td>( Max (TQC_{0j-1} + 2TQ + OQ, TLU_{ki} + T_{a_{ki}^{ij}}))</td>
</tr>
<tr>
<td>U</td>
<td>L</td>
<td>U</td>
<td>( Max (TQC_{0j-1} + TQ + OQ, TLU_{ki} + T_{a_{ki}^{ij}}))</td>
</tr>
<tr>
<td>U</td>
<td>U</td>
<td>L</td>
<td>( Max (TQC_{0j-1} + 2TQ + OQ, TQC_{ki} - TQ - OQ + T_{a_{ki}^{ij}}))</td>
</tr>
<tr>
<td>U</td>
<td>L</td>
<td>L</td>
<td>( Max (TQC_{0j-1} + TQ + OQ, TQC_{ki} - TQ - OQ + T_{a_{ki}^{ij}}))</td>
</tr>
</tbody>
</table>

4 THE PROPOSED SIMULATED ANNEALING ALGORITHM

The integrated scheduling of handling equipment has been proved as an NP-hard problem [13]. Thus, the mathematical programming models are not able to find the optimal solutions for these problems in reasonable computation time, specifically, for the large-scale cases. In this paper, a simulated annealing algorithm is developed to find near optimal solutions for the integrated scheduling of handling equipment including the SP-AS/RS. SAA is a natural inspired algorithm in which the cooling process of metals is imitated [21]. In SAA it is supposed that the environment has an initial temperature (\( T_i \)); and it should reach a steady state called final temperature (\( T_f \)). The temperature is decreased virtually using a cooling process. The SAA searches for individual solutions in each temperature level (\( T_r \)) for a specific number of trials (\( NT \)); and tries to improve the solution through a neighborhood search structure. The algorithm accepts better solutions and in some occasions would accept the worse solutions [12]. However, decrement of the initial temperature would result in lower probability of accepting worse solutions. Expectantly, after a limited number of iterations the SAA will converge to a near optimal solution.
Homayouni et al. [12] have evaluated the influences of various initial temperatures and number of trials in addition to the impacts of three different cooling processes on finding near optimal solutions for integrated scheduling of cranes and vehicles in ACTs. They concluded that the cooling process proposed by Chen and Shahandashti [22] shows better performance for the integrated scheduling problem, and the most appropriate initial temperature and number of trials are 2000 and 50, respectively. The proposed SAA for the integrated scheduling problem of this paper follows these steps to find a near optimal solution for the integrated scheduling problem:

1. Initialize control parameters: $T_i$, $T_f$, and $N_T$;
2. Generate the initial solution, $x$, and evaluate the objective function ($E(x)$);
3. Initialize the inner loop, $r=0$;
   3.1 Generate a new solution $y$ in neighborhood of $x$, and evaluate the objective function ($E(y)$);
   3.2 Calculate $\Delta E = E(x) - E(y)$; If $\Delta E < 0$ then accept the new solution and, make it as the current solution by setting $x = y$. Update the existing optimal solution, go to step 3.4;
   3.3 If $\Delta E \geq 0$ then, $P = \exp\left(-\frac{\Delta E}{T_r}\right)$, If $P \geq \text{rand (0,1)}$ then accept the new solution and, make it the current solution by setting $x = y$;
   3.4 $r=r+1$; If $r > N_T$ then go to step 4, else go to step 3.1;
4 Cool down the current temperature (i.e. $T_r = T_r e^{-\frac{\Delta E}{T_r}}$);
5 If $T_r > T_f$ then go to step 3, else, go to step 6;
6 Terminate the algorithm; print the best solution.

A feasible solution for the problem is defined as a string of tasks for the cranes. As mentioned in the previous section, the tasks of each crane should observe the precedence relations to be feasible. Tasks of cranes are numbered consecutively for the first to the last crane from 1 to $N$ (total number of tasks in the scheduling period). This string of tasks shows the operations should be performed by the SP-AS/RS. However, the platforms of the SP-AS/RS could be scheduled independently. A heuristic algorithm is used to assign the vehicles and platforms of the SP-AS/RS to the tasks using the “earliest available vehicle” rule. In this rule, the vehicle that reaches the starting point of the tasks for both cranes and SP-AS/RS is selected to perform the task.

To find a neighbor solution in the proposed SAA, a swap operator has been designed. In this operator, two tasks of the current string of tasks are selected randomly. Then, it is examined that the subsequent task of the selected first task is located after the second selected task. On the other hand, it is examined that the precedent task of the second selected task is located before the first selected task. If these two statements are true, then the selected tasks can be substituted. Two more rules for this operator can be expressed as followings. If the first selected task is the last task of a crane it can be substituted to the second selected task; and if the second selected task is the first task of a crane it can be transferred to the first selected task.

5 RESULTS OF NUMERICAL TEST CASES

In this section some numerical tests have been designed to evaluate the performance of the proposed scheduling method. The general layout of the ACTs have been designed by Lau and Zhao [9]. In this general layout, there are six QCs, six L/U stations and a determined fleet of AGVs. Travel time between any combination of the L/U stations and the QCs can be found in paper of Lau and Zhao [9]. The operational time of the QCs is set to 20 seconds. The operational time is the average time required for loading (unloading) operations of the cranes to (from) the vessel including the required reshuffling operations. Moreover, travel time of the spread of the QCs between the vessel and the quay side is set to 10 seconds.

The SP-AS/RS as a new storage system is suggested by this paper have not been included in the layout proposed by Lau and Zhao [9]. According to details of the standard dimension of
containers, height and width of the containers are the same. Therefore, it is assumed that each cell of the storage racks including its structure is 3 in 3 meters. The velocity for the HPs and VPs is assumed to be 2 and 1 meter per second (m/sec.), respectively (based on the assumptions of Hu et al. [7] and Vasili et al. [8]). For example, it takes 9 seconds for the HPs to travel from the 6th storage cell to the H/O station. Moreover, each bay of the storage rack consists of 10 rows and 12 columns, or 240 storage cells in total storage rack. This is based on the assumptions of Liu et al. [23]. Thus, based on the proposed specifications for the SP-AS/RS, height of the storage racks is 30 meters, and its width is 36 meters.

To verify the true results found by the proposed SAA, the respective results found by this algorithm is compared to the results obtained by the proposed MIP model. Six small size test cases have been designed in which 8 to 16 loading/unloading tasks were assigned to 2 or three QCs. Moreover, according to the number of tasks, a predetermined number of AGVs were assigned to perform these tasks. The specifications of the small size numerical test cases are presented in table 5. The storage cells for these tasks have been determined, too. Using the proposed integrated scheduling method, the sequence of tasks for each AGV, VP, and HP has been determined, and the exact event times for any operation of the loading/unloading tasks were calculated. Then, the objective function of the proposed optimization methods (including to minimize delays in QCs’ tasks, and travelling time of the AGVs, VPs, and HPs) for the small size test cases have been calculated and reported in table 5.

### Table 5: Optimal And Near Optimal Solutions For The Small Size Test Cases

<table>
<thead>
<tr>
<th>No.</th>
<th>Specifications</th>
<th>MIP Model</th>
<th>SA Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>8-2-2-3</td>
<td>371/294</td>
<td>873.3</td>
</tr>
<tr>
<td>S2</td>
<td>9-3-3-2</td>
<td>463/344</td>
<td>951.2</td>
</tr>
<tr>
<td>S3</td>
<td>10-2-2-5</td>
<td>520/418</td>
<td>729.5</td>
</tr>
<tr>
<td>S4</td>
<td>12-2-2-6</td>
<td>672/576</td>
<td>948</td>
</tr>
<tr>
<td>S5</td>
<td>15-3-3-5</td>
<td>826/692</td>
<td>1175.6</td>
</tr>
<tr>
<td>S6</td>
<td>16-4-4-4</td>
<td>904/747</td>
<td>2388.5*</td>
</tr>
</tbody>
</table>

“Dec. Var.”, in table 5, shows number of decision variables/ integer variables of each test case. The data demonstrate that as the number of tasks per QC increases the number of decision variables increases, exponentially. Higher number of decision variables result in longer CPU time for the MIP model to find the optimal solution of the problem. However, for test case S6, the MIP model is unable to find an optimal solution after more than 9 hours of calculations. The last feasible solution for this test case were recorded in table 5 and signed by an asterisk.

These test cases were solved by the proposed SAA for 10 replications. The mean of objective value for the 10 replications and the best-obtained objective values for the SAA are reported in table 5. The “Opt. Gap” shows the percentage differences between the optimal solution of the test cases and its near optimal solution found by the SAA. The average optimality gap between the MIP model and the SAA for these test cases is 2.9% which demonstrates that the SAA is able to find very near optimal solutions for the integrated scheduling of handling equipment in the ACTs. Moreover, the CPU time for the SAA, recorded in table 5, shows that while the MIP needs much longer time to find a solution, the SAA is able to find good solutions for the problem, in reasonable CPU time.

The second test describes how integrated and non-integrated scheduling methods are different in small size test cases. The solutions obtained by the MIP model are compared to the results obtained by using the regular heuristic rule of “first-come-first-served”, in which, the AGVs, VPs, and HPs are assigned to the task, only based on the sequence of tasks for the QCs. The results are tabulated in Table 6, in which, three objectives of the model are
presented for both methods, in addition to the overall objective function. “TD”, “TT”, and “THV” denotes total delays in tasks of QCs, total travel time of the AGVs, and total travel time of VPs and HPs, respectively.

“Deviation” in table 6 is the percentage differences between the objective value of the non-integrated scheduling method and objective value of the proposed integrated scheduling method. The results indicate that, on average, objective value of the non-integrated scheduling method is 58% more than that for the integrated scheduling method. According to table 6, on average, total travel time of AGVs and total travel time for VPs and HPs for the non-integrated scheduling method are 16.8% and 17.3% more than those for the proposed scheduling method, respectively. However, total delays in cranes’ tasks in non-integrated scheduling method are 74.6% more than that for the integrated scheduling method. Obviously, changing the sequence of cranes’ tasks, considering the operational time of other handling equipment, results in a great improvement for the delays of loading and unloading tasks.

<table>
<thead>
<tr>
<th>No.</th>
<th>Integrated Scheduling</th>
<th>Non-Integrated Scheduling</th>
<th>Deviation%</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD</td>
<td>TT</td>
<td>THV</td>
<td>TD</td>
</tr>
<tr>
<td>S1</td>
<td>873.3</td>
<td></td>
<td>1176.3</td>
</tr>
<tr>
<td>830 S</td>
<td>1740 S</td>
<td>353 S</td>
<td>1169 S</td>
</tr>
<tr>
<td>S2</td>
<td>951.2</td>
<td></td>
<td>1715.1</td>
</tr>
<tr>
<td>965 S</td>
<td>1370 S</td>
<td>422 S</td>
<td>1869 S</td>
</tr>
<tr>
<td>S3</td>
<td>729.5</td>
<td></td>
<td>1137</td>
</tr>
<tr>
<td>568 S</td>
<td>2200 S</td>
<td>551 S</td>
<td>1032 S</td>
</tr>
<tr>
<td>S4</td>
<td>948</td>
<td></td>
<td>2062</td>
</tr>
<tr>
<td>936 S</td>
<td>3040 S</td>
<td>552 S</td>
<td>1992 S</td>
</tr>
<tr>
<td>S5</td>
<td>1175.6</td>
<td></td>
<td>1753.6</td>
</tr>
<tr>
<td>995 S</td>
<td>3040 S</td>
<td>756 S</td>
<td>1668 S</td>
</tr>
<tr>
<td>S6</td>
<td>2388.5</td>
<td></td>
<td>3421.9</td>
</tr>
<tr>
<td>2430 S</td>
<td>3832 S</td>
<td>613 S</td>
<td>3643 S</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>58.05%</td>
</tr>
</tbody>
</table>

In a set of large size tests, the impact of number of AGVs on the performance of the scheduling method is investigated. Five large test cases, with 64 to 95 tasks assigned to four to five QCs were designed. The number of available AGVs changes 6 to 20 in the scheduling period. Any of the test cases have been solved for 10 replications of the proposed SAA under any number of AGVs and the mean of overall objective values are graphed in figure 2.a. Results presented in figure 2.a. illustrates that the objective function of the integrated scheduling of handling equipment decreases as the number of vehicles increases. However, this reduction is more substantial in lower number of vehicles; and after reaching a certain number of vehicles (e.g. 12 for test cases L1 and L2); the reduction is not considerable any more. The findings of this test are supported by the respective results carried out by Lau and Zhao [9]. They explained that unlimited increasing the number of available AGVs would not results in unlimited decreasing for the value of the objective function.

The integrated scheduling is a multi-objective problem. Mean of three individual objectives of the integrated scheduling method for this test are drawn in figure 2.b to 2.d. Evidently,
total travel time of the AGVs increases as the number of available AGVs increases (figure 2.b), while delays in cranes' tasks decrease in the same trend as total objective function of the problem (Figure 2.b). On the other hand, total travel time of the HPs and VPs does not change greatly by increasing the number of AGVs. This means that more AGVs travel longer routes to decrease delays in cranes' tasks which have a higher weight in the objective function of the integrated scheduling of handling equipment.

![Figure 2: Impact Of Number Of Available AGVs On Objectives Of The Integrated Scheduling Method](image)

Moreover, effects of number of available AGVs were examined on the non-integrated scheduling method, based on the first come first served FCFS heuristic rule, in the large size test cases. From the results of this test, one can conclude that on average, half of the number of AGVs is required under the integrated scheduling method, to achieve similar objective value to the non-integrated scheduling method. A similar test have been conducted by Vis and Roodbergen [24] based on the first come first served heuristic rule for the operations of the straddle carriers. They concluded that based on their optimal scheduling method almost 60% of the number of straddle carriers are required to perform the same sequence of tasks compared against this heuristic rule.

6 DISCUSSION AND CONCLUSION

In this paper, an integrated scheduling method for handling equipment including the SP-AS/RS in automated container terminals. Using this new storage system in the ACTs decreases the operational time of the storage yard compared against the automated stacking cranes. Moreover, using two platforms in the SP-AS/RS make the scheduling process more flexible. Therefore, the overall time to load or unload a vessel along with delays in tasks of QCs can be decreased. On the other hand, a new mixed integer-programming model for the problem has been developed, in order to optimize the integrated scheduling of handling equipment. This MIP model can be used in future studies for comparison purposes. Furthermore, an algorithm based on the principles of the simulated annealing algorithm was developed to optimize the integrated scheduling of handling equipment. It is recommended for future studies to include automated lifting vehicles in the integrated scheduling problems. Moreover, development of methods for rescheduling in cases that an unpredicted phenomenon (e.g. failure in any of the equipment) avoids continuing the current schedule is suggested for future studies.
7 REFERENCES


