Optimization of Container Handling Systems in Automated Maritime Terminal

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Abstract. Container terminals play a crucial role in global logistic networks. Because of the ever-increasing quantity of cargo, terminal operators need solutions for different decisional problems. In the maritime terminal, at boat arrival or departure, we observe five main problems: the allocation of berths, the allocation of query cranes, the allocation of storage space, the optimization of stacking cranes work load and the scheduling and routing of vehicles. A good cooperation between the different installations in the terminal is important in order to minimize container handling time. In an automated container terminal using Automated Guided Vehicles (AGVs) Query Cranes (QCs) and Automated Stacking Cranes (ASCs) numerical solutions have become essential to optimize operators' decisions. Many recent researches have discussed the optimization of ACT equipment scheduling using different approaches. In this paper we propose three mathematical models and an exact resolution of QC-AGV-ASC planning, the problem of tasks in an automated container terminal. Our first objective is to minimize the makespan (the time when the last task is achieved). The second objective is to minimize the number of required vehicles.

1 Introduction

In an automated container terminal (ACT) the time of handling operations depends on the interactions between the different storage equipments. Different researches are established to improve the handling systems performance. We will interest next to the problems which consider our two objectives (minimizing the makespan and minimizing the AGV fleet size). These two objectives are treated in the AGV scheduling problem. The problem of AGV scheduling was treated in the general context of AGVS and in the particular context of ACT. AGVS is a materials handling system that uses automated vehicles which are programmed to achieve missions between different manufacturing and warehouse stations . It represents a very important innovation in international transport and logistics. ACT is one of the most famous examples of AGVS. Studies of AGVS optimization have different objectives: maximizing the throughput, maximizing the vehicle utilization, minimizing the inventory level, minimizing the transportation costs, and maximizing the space utilization. AGVS mathematical models have to respect some conditions to eliminate the traffic

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problems. Approaches used in AGVS optimization can be classified in two kinds: analytical approaches and simulation-based approaches. Analytical methods are mathematical techniques such as queuing theory, integer programming, heuristic algorithm, and Markov Chains. A number of analytical approaches to AGVS optimization have been proposed in the literature.

1.1 Problems of Minimizing AGV Fleet Size in AGVS and ACT

AGVs historically have not been produced in high volume. Then in AGVS determining the minimum number of vehicles required to achieve a set of tasks in efficient and economic way is crucial to improve the global system productivity. Muller[2] used rough estimates of total AGV travel times and transport frequency to resolve the AGV system case. The team of Maxwell and Muckstadt [3] discuss the deterministic case of the problem. They consider the random aspect of the problem: variation of arrival pattern of jobs and vehicles speed and they developed an integer programming formulation to minimize the number of required AGVs. In Rajota et al [4] other parameters are considered: load handling times, empty travel time… The team developed a mixed integer programming model. Sinriech and Tanchoco [5] have developed a multi-objective model which keep the total cost of AGV system down and increases the system utilization. The problem is treated by I FA Vis [6], in the ACT context he developed new planning concepts to minimize the AGV fleet size and he applied it to the container terminal case considering a deterministic model with defined time windows for each container load. He proposed two methods to solve the problem: an integer programming model and a formulation of the problem as a set of partitioning sub problem.

1.2 Minimizing Vehicle Fleet Size in Other Contexts

Two analog problems are discussed in literature. The first problem is the determination of the minimum number of operators required to accomplish a known schedule of tasks. This problem was treated by Phillips and Garcia-Diaz [7]. They use a bipartite network where the maximum flow indicates pairs of tasks assigned to the same operator. Then they propose the research of arcs of the maximum flow to obtain the list of tasks for each operator. Ford and Fulkurson [8] discus this problem and use a partial order of tasks: tasks i precedes task j if the start time of i is earlier than the start time of j and if the two tasks can be achieved by the same operator. They resolve the problem with the determination of minimum chain decomposition. The second analog problem is the tanker scheduling. Dantizig and Fulkerson [9] describe a deterministic model to solve the tanker scheduling problem with linear programming formulation and simplex algorithm. Ahuja et al [10] propose another approach to resolve the same problem: they introduce a minimum cost flow formulation of the problem and use a minimum cost flow algorithm to minimize the fleet size of the main problem.

1.3 Problems of Minimizing Makespan in AGVS and ACT

The problem of minimizing makespan is treated in the general AGVS context. In 1984 Ebeglu and Tanchoco [11] developed a dispatching rules method for AGVs scheduling. Tanchoco et al. [12] discussed real-time control strategies for multiple-load AGVs. Models and methods applied to AGVS seem to be generally applicable and need to be adjusted for more specific contexts. The researches of minimizing makespan in ACT are recent especially with the integrated aspect of QC-AGV-ASC problem (AGV or ALV). Chen et al. [13] treated the scheduling of AGVs. They developed a dispatching approach and simplified the QC task considering it available to AGV loading or unloading which cannot' assure the solution optimality for the multiples QCs case. Kim and Bae[14] developed a model with fixed pick up time for each container and they proposed heuristic solution for more general cases. Meersman [1] was perhaps the first researcher to consider the integrated QCs, AGV and ASC scheduling problem. He showed that this problem is NP-Hard and developed mathematical theorems for the problem of scheduling ASC-AGV-QC tasks. He studied static traffic layout (layout with one fixed path for each task) and dynamic traffic layout (layout with different possible paths for each task). Meersman used branch and bound and beam search algorithms to resolve the static traffic case using mathematical theorem results to establish valid inequalities. Bae et al [15] developed a dynamic berth scheduling method for minimizing the cost of the vehicles travel during the loading or unloading of ship. The approach take into account many constraints and real dynamic situations.

1.4 Multi-criteria AGVS Scheduling Models

With the increasing automation of manufacturing systems, the use of efficient and multi-criteria decision systems is very important to optimize productivity. AGV systems seem to be the most famous example. A good evaluation of the cost of AGVS must take into account different characteristics: vehicle dispatch, load and unload central controller, complex host interface, product tracking, multiple paths layout etc. In 1981 Dahlstrom and Maskin [16] and Muller [17] have addressed the economical aspects of AGVS; the two papers compared the cost of different material handling systems. Sinriech and Tanchoco [18] have developed a multi-objective model which keep the total cost of AGVS down and increases the utilization of the system. They assume that AGVS cost is a formulation of operating costs (maintenance, energy...) and design costs (vehicle supervisory controller, vehicles, batteries, chargers, communication links etc).

In the next parts we propose solutions for three terminal layouts and we use Meersman's results [1] to improve the mathematical modeling and the quality of our numerical solutions. We propose a model with two objectives: the optimization of task time for the QC-AGV-ASC problem and the minimization of the number of vehicles used. We use Meersman's mathematical results to perform our modeling and resolution and we propose new models for the scheduling problem using a partial container' order and resolving large problem instances. Different automated terminal layouts can be studied. Meersman presents two possible port architectures: a simple layout with static AGV traffic and a complex layout with multiple variable paths. Another case is studied by Vu D N and Kap H.K [19]; we can describe this case as a multiple fixed paths layout. In this paper we will look at the three layout cases and propose mathematical modeling adapted for each case. Then we will give the simulation results that we obtain after using Meersman's theorem of partial order (cf. part 4).

2 Terminal Architectures

In this part we use a notion of ASC Points and QC Points: ASC Points are the places where ASCs pick up containers from AGVs and QC Points are the places where QCs loads containers on the vehicles (these notions will be used in the next parts). For the two first models we consider also Point A as a final position in the path for every task.

We consider three terminal layout possibilities.

2.1 One-Path Layout

The model supposes static AGV traffic and does not take into account traffic security.

We consider that all AGVs have the same path for each task.

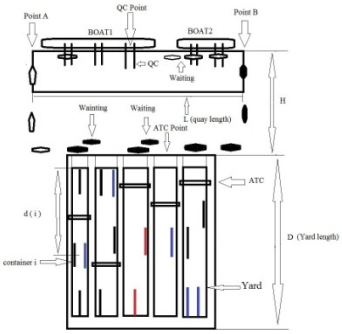

Fig. 1. One-Path layout

We can describe this case as a one-path layout. We consider the import case and the export case as symmetric and the scheduling problem is the same. In Fig.1 black vehicles represent the loaded AGVs and white vehicles the unloaded AGVs. Point A is the final point of every task. All AGVs have the same task path. We assume that the terminal's routes have two possible directions and that many AGVs can use the same path at the same time without risks. The AGVs start at QC point, then go to point B, then to the ASC point (where there is a possible waiting time) and finally they return to point A. Before starting its task, every AGV has to wait until the end of the last QC task.

With this model of terminal layout the optimization can minimize only the sum of waiting time at the QC and ASC points, the AGV paths are known and static. This layout is treated by Chang Ho Yang and all [16].

2.2 Multiple Fixed Paths Layout

Point A (show Fig.2) is the final point of every task. All AGVs have a known task path; they start at QC Point then choose the shortest path to the ASC Point, finally going to point A. The paths are not the same for all tasks but each path is initially known, they depend only on the ASC and QC positions. Before starting its tasks, every AGV has to wait sufficient time so as not to cause an accident with the predecessor AGV at QC.

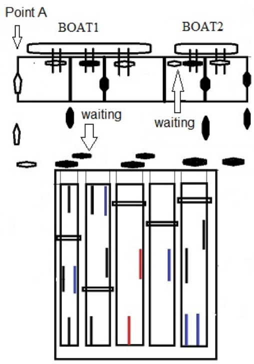

Fig. 2. Multiple fixed paths layout

With this model of terminal architecture we have to minimize only the sum of waiting times at the QC and ASC Points, because AGV routing are initially known.

For the two first cases (one-path and multiple fixed paths layouts), we optimize the AGV scheduling problem with the same linear model.

2.3 Multiple Variable Paths Layout

This third case is the most complex architectural model. The travel times are variable and unknown because for each task the AGV does not return to a common final point (Point A in FIG.2 and FIG.1) but moves directly to its next task. The travel time between the present task and the next is unknown and depends on the choice of the next task.

In the static and the semi-dynamic traffic model when we optimize container handling time, only the waiting time is important because in each case we can choose the first AGV (returned to Point A) for the next task .In the dynamic traffic case, the choice of AGV for some tasks is important because AGVs do not finish their tasks at the same point. Thus choosing the first free AGV for the next task is not a good idea: we have to release a double scheduling (TASKi, AGVj) if we resolve the problem with a branch and bound algorithm.

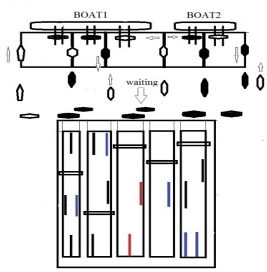

Fig. 3. Multiple variable paths layout

3 Data Generation

Data generation is based on terminal architecture and the handling speed of equipment.

In Fig.1, we demonstrate the distances which we use to generate data: L the quay length, D the yard length, H the distance between quay and storage zone.

The AGV and ASC transfer speed combined with the terminal dimensions give a clear idea about the data that we need for our modeling and simulations.

4 Important Theorem

Meersman [1] used a strategy of partial order to resolve large instances of the scheduling problem: the tasks of each ASC are totally ordered. He supposes a sufficient quantity of AGVs which can ensure an optimal schedule and he concluded an important theorem.

"Define the assignment order Π as the order in which the containers are assigned to the AGVs as they pass the common point. Moreover, define a suborder Πs as a subset of Π, such that if i is ordered before j in Πs, then i is ordered before j in Π, for all i, j Є Πs. Theorem: For each ASC s Є S, consider an optimal schedule. Let Πs denote the order in which ASC s handles its containers. Then there exists an optimal assignment order Π, such that Πs is a suborder of Π."

5 Mathematical Models

In parts 5.2 and 5.3, we consider that the number of AGVs is sufficient to complete an optimal schedule. We consider a total order in each set of ASC tasks and another total order in each set of QC tasks (we use models with buffer space of QC equal to 1). Then the set of all tasks has a partial order and for any task i the successor task and predecessor task in QC and the successor task and predecessor task in ASC are initially known. In the next part we consider that the matrixes ASCi,j and QCi,j are constant.

We define the following variables for all models.

V: the set of AGVs (Automated Guided Vehicles)
C: the set of ASCs (Automated Stacking Crane)
Q: the set of QCs (Query Crane)
M: the set of tasks
$AGV_{i,j}$: decision variable, if the container j is handled directly after the container i by the same AGV $AGV_{i,j}$ =1 else $AGV_{i,j}$ = 0
$QC_{i,j}$: If task i is succeeded directly by j in the same QC, $QC_{i,j}$ = 1 else $QC_{i,j}$ = 0, we consider this data known.
$ASC_{i,j}$: If task i is succeeded directly by j in the same ASC $ASC_{i,j}$= 1 else $ASC_{i,j}$ =0.We apply Meersman's theorem and we choose the order of tasks for every ASC (ASC order must respect QC order).

$T_{1,i}$: the travel time between the start point and the ASC point
$T_{2,i}$: the travel time between the ASC point and the final point
$T_{qc,i}$: the travel time between point A and QC Point
S_i: the ASC transfer time of task i (depend on ASC speed and d(i) (Fig.1))
$t_1(i)$: the start time of task i
$t_2(i)$: the completion time of task i
S_{qc}:the time that QC need to load container on AGV
S_{asc}: the time that ASC need to pick up container
S_s: safety waiting time (near QC Point).

t_0: start time.

5.1 Formulation of the Number of Used Vehicles

Consider |M| the number of tasks and |V| the number of AGVs, then:

$$|M| - \sum_{i \in M} \sum_{j \in M} AGV_{i,j} = |V|$$

Dem: $\sum_{i \in M} \sum_{j \in M} AGV_{i,j}$ is equal to the number of containers (or tasks) having direct predecessor in AGV then $|M| - \sum_{i \in M} \sum_{j \in M} AGV_{i,j}$ is equal to the number of containers or tasks not having a direct successor. A task with no direct successor is a first task for a fixed AGV then the number of those tasks is equal to the number of AGVs.

5.2 One-Path and Multiple Fixed Paths Mathematical Model

$$Min \max \{t_2(i)/i \in M\} \tag{1}$$

$$\sum_{j \in M} AGV_{i,j} \leq 1, \qquad \forall i \in M \tag{2}$$

$$\sum_{j \in M} AGV_{j,i} \leq 1, \qquad \forall i \in M \tag{3}$$

$$\sum_{i \in M} \sum_{j \in M} AGV_{i,j} = |M| - |V| \tag{4}$$

$$AGV_{i,i} = 0, \qquad \forall i \in M \tag{5}$$

$$t_1(i) \geq t_0\,, \quad \forall i \in M \tag{6}$$

$$t_1(i) + G\left(1 - \mathrm{AGV_{j,i}}\right) \geq t_2(j) + T_{qc,i}\ , \qquad \forall i, j \in M \tag{7}$$

$$\forall i, j \in M / ASC_{j,i} = 1 :$$

$$t_2(i) = \max\left(t_1(i) + S_{qc} + T_{1,i} + S_{asc} + T_{2,i}\ , \left(t_2(j) - T_{2,j} + s_i\right)\right) \tag{8}$$

$$t_1(i) \geq QC_{i,j}(t_1(j) + S_{qc} + S_s), \qquad \forall i, j \in M \tag{9}$$

Constraint 1: minimize the completion time of the last tasks.
Constraints 2 and 3: limit the number of direct successor and direct predecessor, every container has one or zero direct successor and one or zero direct predecessor.
Constraint 4: if we use k AGVs , k containers will have exactly zero successor and k containers will have exactly zero predecessor because every AGV will have a first task and a last task(final task for it).Then for n containers, only n-k missions will be succeeded and only n-k missions will be preceded.
Constraint 5: No container can precede or succeed itself.
Constraint 6: No mission can start before t0.
Constraint 7: Relation between two successive tasks of an AGV. If container j is handled directly after containers i with the same AGV, then AGVi,j = 1 and we have:
t1(j) ≥ t2(i)+$T_{qc,j}$ or else the relation will be: t1(j) + G ≥ t2(i) +$T_{qc,j}$ and that is true because G is sufficiently large.
Constraint 8: This constraint is a result of 2 other constraints:

- t2 (i) ≥ t1 (i) +T1,i + Sqc + Sasc + T2,i : the final time of any mission is equal or greater than the start mission time plus the travel time plus the QC loading time plus the ASC loading time.
- V i,j Є M: t2 (j) - T2,j - Sasc ≥ QCi,j (t2(i) - T2,i + S(i)): t2 (j) - T2,j - Sasc is the start time of the ASC task j. t2(i) - T2,i + S(i): completion time of i.

Constraint 9: the difference between 2 successive QC tasks is greater than or equal to the loading time at QC plus a safety time.

5.3 Multiple Variable Paths Mathematical Model

$Y_{j,i}$ is the travel time between the final point of task j (ASC point) and the first point of task i (QC point). If we consider the first model we change only constraints (7) and (8) to obtain the dynamic traffic model.

$$\text{Min max}\,\{t_2(i)/i \in M\}$$

Constraints (2) to (6) and constraint (9) of the static traffic model

$$t_2(i) = \max\Big(t_1(i) + S_{qc} + T_{1,i} + S_{asc}, (t_2(j) + s_i + s_{asc})\Big), \forall i,j \in M/ASC_{j,i} = 1 \quad (10)$$

$$t_1(i) + G\big(1 - AGV_{j,i}\big) \geq t_2(j) + Y_{j,i}, \ \forall i,j \in M \quad (11)$$

5.4 Bi-objective Model

To resolve correctly the scheduling problem using the theorem of sub-orders, we need to use a sufficient number of AGVs for the optimal schedule. This number will depend on the travel distances, the AGV transfer speed and ASC transfer speed .In next model we can naturally use the theorem of the sub-orders because the minimal numbers of AGVs that we search has to satisfy the time optimality. In 2001 IFA's team developed a minimum flow algorithm to determine the number of AGVs required at a semi automated container terminal [6]. Our be-objective model is a good solution to resolve the scheduling problem in short run time and giving a small numbers off AGVs required. The value of k is important to resolve the problem; it depends on the number of tasks and on the equipment speed. and we have to choice a sufficiently great value. We replace (1) by (12) and (4) by (13) and (4) We obtain a new model which is more efficient and more intelligent. This model has two objectives: minimize the completion time of the last task and minimize the number of AGV necessary to complete the optimal scheduling. Constraints (2), (3), (4), (7) and (8) of the dynamic traffic model are used for this model.

$$Min\ (k \max\{t_2(i)/i \in M\} + \ (|M| - \sum_{i \in M}\sum_{j \in M} AGV_{i,j}) \quad (12)$$

$$\sum_{i \in M}\sum_{j \in M} AGV_{i,j} \leq |M| - 1 \quad (13)$$

6 Cplex Results

We choose cplex optimizer to test the performance of the models. The application of the sub-orders theorem combined with the use of constraint (4) give a possibility to resolve instances of hundreds of containers but with a use of a number of AGVs more than 10 per cent of the containers number. Using the third model we can resolve the scheduling problem with a small AGV set because the model has two objectives: minimize containers handling and transfer time and minimize the number of AGVs used. We resolve problem instances of 10 to 500 containers with a GAP of 0.15 to 0 percent. One of our most important results was the resolution of the bi-objective problems (minimizing stacking time and AGV resources) of 500 containers, 3 QC and 8 ASC. The GAP is not stable, the AGV and ATC speed and the paths routing time for some instances can increasing the GAP value. With the first presented model, using sufficient AGVs numbers (between 10 and 15 percent of the tasks numbers) we resolve small and big problem instances with optimal solution. The third model (two-objective model) is more efficacies for the instance with a limited numbers of vehicles. Results depend on the layout model: For the one-path layout problem instances less than 150 containers are generally easily resolved and the two objectives are reached with double optimality (Table 2). For the multiple variable paths layout problem instances the double optimality is harder and the run time is larger compared with the static case.

Table 1. LMAH-Model (with Cplex resolution) resolution compared to Meersman model (with branch and bound resolution)

	LMAH-Model	Meersman
Objectif(s)	2 objectives: minimizing "makespan" and minimizing AGV fleet size.	1 objectif: minimizing "makespane"
equipments	QC-AGV-ASC	QC-AGV-ASC
performance	A gap of 0 % for instances up to 500 containers 4 QCs and 12 ASCs. For these instances the runtime is between 0s and 60s	A gap of 0% to 8% for instances up to 170 containers up to 170 containers 27 ASCs and 24 AGVs. For these instances the runtime is between 0s and 658s
conditions	Consider a sufficient number of AGVs (optimal number) Consider the QC task as an AGV loading (time-lags)	Consider the QC task as an AGV loading (time-lags)

Table 2. Results of bi-objective modeling in the static traffic case Table 1. Results of bi-objective modeling with the one-path layout.

Instance	k	Makespan gap	Fleet size	Total gap	Run time
150/3/6	1	0%	18*	0%	4 s
250/4/12	1	0%	21*	0%	6 s
500/4/8	1	0%	23	0.11%	60 s

(*): optimal value Instance: number of containers / number of QCs / number of ASCs.

7 Conclusion

A new generation of terminal using automated container handling equipment needs solutions to optimize task scheduling and operating costs. Many storage strategies, statistical studies, mathematical models and algorithms are proposed by researchers. To resolve the planning of QC-AGV-ASC, we present an effective model for every kind of traffic layout. We propose an efficient bi-objective model, which is important to determine the optimal storage time and the minimal number of AGVs required. The bi-objective model can resolve large instances (up to 500 containers) with double optimality (giving the optimal makespan and the minimum number of required AGVs) in reasonable run time (less than 60 s). Our bi-objective model is perhaps the first model optimizing in on time the makespan and the AGV fleet size in a container terminal. Our models consider 3 types of handling equipment (AGV, QC and ASC) which is an efficient approach. For future works we will discuss metaheuristic programming resolutions and dispatching rules of a more advanced multi-criteria model.

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