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Study on Quay Crane Allocation Problem for Thevessels Withdifferent Priorities in Container Terminals

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Abstract: Thedecisionofquay craneschedulingproblemis crucialforport operators in port container terminals. In this study, in view of analysis and summary of general experience in the quay-crane resource allocation, such allocation problem in container terminals is proposed on the basis of advance rule,namely, how to assign limited quay cranes for berthing vessels while meeting the requirement of handling workloads and its distribution, in-port turnaround time, dispatching fees and other factors. According to the features of loading and unloading operations in container terminals, an integer programming model is established for quaycrane allocation problem and then corresponding solver is developed by AIMMS tool. The practicality and effectiveness of the model is demonstrated by large amounts of case study and the robustness of algorithm is testified to be feasible. The utilization of this decision model can improve the overall performance of quay cranes,reducehandling cost and enhance operational efficiency.

Key words: Container terminal, quay crane allocation, different priorities,operational efficiency

INTRODUCTION

Under the circumstance of global economic and trade development, the overwhelming majority of general cargo is nowadays containerized and mega-containerships are graduallyput into use in the container transportation system.

Currently in our country, dwelling ships are of common occurrence in many large-scale container ports. One reason lies in the fact that the capacity of ports cannot keep pace with logistic development while another important cause is that the resources in the port are not scheduled in a scientific and reasonable way which reduces service capability. Operational problems in container terminals are typical of multi-objectives, uncertainty and complexity in decision-making. During loading and unloading processes in container terminals, quay cranes are expensive and limited equipment resources, hence quay-crane allocation largely restricts the overall handling efficiency. Reasonable quay-crane allocation is the prerequisite to utmost utilization of mechanical equipment such as quay cranes, container trucks and yard cranes and also rational assignment is the pre-order operation of quay crane scheduling, container truck scheduling and yard crane scheduling.

In the field of quay-crane allocation problem, many scholars at home and abroad proposed various kinds of models and algorithms.

Lu *et al*. (2012) proposed the concept of contiguous bay operations and developed a heuristic algorithm to generate QC schedules with this feature. Their heuristic was efficient with polynomial computational complexity and could produce schedules with a completion time objective bounded above by a small increment over the optimal completion time. And the heuristic guaranteed that no quay cranes are idle. Chung and Choy (2012) proposed a modified genetic algorithm to deal withthe problem. The result demonstrated that the proposed algorithm performed as good as many existingalgorithms and obtained better solutions than the best known ones in certain instances. Bierwirth and Meisel (2010) tried to provide a support in modelingproblem characteristics and in suggesting applicable algorithms this study reviews the relevant literature. New classification schemes for berth allocation problems and quay cranescheduling problems were developed. Particular focus was put on integrated approaches whichreceived increasing importance for the terminal management. Tavakkoli-Moghaddam *et al*. (2009) presented a novel, Mixed-Integer Programming (MIP) model for the Quay Crane (QC) schedulingand assignment problem, namely QCSAP, in a container port (terminal).

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They proposed a Genetic Algorithm (GA) to solve the above-mentioned QCSAP for the real-world situations. Further, the efficiency of the proposedGA was compared against the LINGO software package in terms of computational times for small-sizedproblems. The computational results suggested that the proposed GA was able to solve the QCSAP, especially for large sizes. Kaveshgar *et al*. (2012) addressed the Quay Crane Scheduling Problem (QCSP) which was shown to be NP-complete.They extended the research in this area by utilizing the GAthat was available in the latest version of Global Optimization Toolbox in MATLAB 7.13 to facilitate development which is aimed to improve the efficiency of the GA search. Meisel and Bierwirth (2011) presented anewplat form for thec omparison of models and algorithms with applicationtoquaycrane scheduling. It provided ascalable, reproducible, and unbiasedtest environment which reflected many important features of crane scheduling that were met inpracticeas well as inresearch. Intotal, 400 testinstanceshad beengenerated and solved by apowerful heuristic which could serveasabenchmark for futures earchin the field. Unsal and Oguz (2013) proposed a Constraint Programming (CP) model for the Quay Crane Schedulingproblem (QCSP) with realistic constraints such asafety margins, travel times and precedence relations. And QCSP with time windowsand integrated crane assignment and scheduling problem were discussed. The performanceof the CP model was compared with that of algorithms presented in QCSP literature. Chen *et al*. (2011)discussed quay crane scheduling problem at indented berth, an extension tothe current quay crane scheduling problem in the field of container terminal operation. Amixed integer programmingmodel was formulated. Decomposition heuristicframework was developed and enhanced by tabu search. Exposito-Izquierdo *et al*. (2013) presented a hybrid estimation of distribution algorithm with local search to solve the QCSP. This approach included a priori knowledge aboutthe problem in the initialization step to reach promising regions of the search space as well as a novelrestarting strategy with the aim of avoiding the premature convergence of the search. Furthermore, anapproximate evaluation scheme was applied in order to reduce the computational burden. Moreover itsperformance was statistically compared with the best optimization method from the literature. Nguyen *et al*. (2013) developed a new priority-based schedule construction procedure to generate quay crane schedules. From this procedure, two new hybrid evolutionary computation methods based on Genetic Algorithm (GA) and Genetic Programming (GP) were developed. The key difference between the two methods was their representations which decided how priorities of tasks were determined. While GA employed a permutation representation to decide the priorities of tasks, GP represented its individuals as a priority function which was used to calculate the priorities of tasks. A local search heuristic was also proposed to improve the quality of solutions obtained by GA and GP. Zhang and Kim (2009) attempted to minimize the number of operation cycles of a QC for discharging andloading containers in a ship-bay. A formulation in QC scheduling problems was proposed as a mixedinteger programming model and a hybrid heuristic approach was employed to solve this model. Legato *et al*. (2012) provided a rich model for quay crane scheduling that covered important issues of practical relevance like crane-individual service rates, ready times and due dates for cranes, safety requirements and precedence relations among container groups. For solving the problem, they employed a branch-and-bound scheme that was known to be the best available solution method for a class of less rich quay crane scheduling problems. This scheme was extended by revising and extending the contained lower bounds and branching criteria. Moreover, a novel Timed Petri Net approach was developed and incorporated into the scheme for determining the starting times of the discharge and load operations in a schedule. Zhang *et al*. (2010) examined the allocation of berths and quay cranes for vessels arriving at container terminals.They took into consideration the coverage ranges of quay cranes and allows for limited adjustmentsof quay cranes during loading and discharging. A mixed integer programming model was constructed and a sub-gradient optimization algorithm was applied to solving the problem.Wang and Hu (2009) advocated the application of Ant Colony Algorithm to study the quay crane resource allocation model. Chen *et al*. (2006) proposed an integrated scheduling model based on a flexible flow shop. Because of NP (non-polynomial) hard problem, two types of heuristic algorithms based on priority rules were developed to solve the problem. Allocation of different kinds of handling equipment in an integrated way can improve coordination among different equipment,increase overall performance of terminals and decrease operational cost. Experiments show that the algorithms can solve addressed problem effectively. Sammarra *et al*. (2007) proposed a tabusearch heuristic to accomplish loading and unloading operations in a minimum completion time. The effectiveness of the algorithm was assessed by comparing it with a branch-and-cut algorithm and a Greedy Randomized Adaptive Search Procedure.

All in all, no research work has been conducted on advance rule, balance principle and effect on quay-cranescheduling in later period which is the scope of this study. On account of this, the related elements are carefully taken into consideration.

The rest of study is organized as follows. Section 2 defines the problem we address in this study. In section 3, a detailed illustration to the proposed model is given which is oriented to quay crane scheduling. Thereafter, solution procedure and computational results are presented in Section 4. Conclusions are discussed in Section 5.

PROBLEM DEFINITION

With the fast development of computer technology and ever-growing demand for container transportation and handling efficiency, modern management information systems for vessel stowage have been widely adopted and applied in container terminals all around the world.

Quay Cranes (QC) are key resources at container terminals and the efficiency of QC operations is vital for terminal productivity. The Quay Crane Scheduling Problem (QCSP) is to schedule the work activities for a set of cranes assigned to a single berthed vessel with the objective of minimizing the completion time of all container handling tasks. The problem is complicated by special characteristics of QC operations.

Quay-crane allocation must follow certain principles and main principles are listed as follows:

- Quay cranes are allocated according to loading and unloading tasks of vessels

Task is equal to the required quantity of loading and unloading containers. As the operations are conducted by quay-cranes, the amount of tasks is counted by hooks or moves in logistic terms. Usually the unloading operation of one container equals one hook. The loading process involves container release in the yard which is restricted by yard position, thus leading to delays of container trucks or traffic congestion. The efficiency of loading is lower than that of unloading process and so real loading workload is equivalent to the loading task multiplied by a coefficient (usually 1.3). And moreover, in case of time limitation and delay in shipping date, an allowance (usually 5%) should be added to initial sum of loading and unloading tasks.

- Quay cranes are allocated according to shipping date

Although handling tasks of each vessel is not the same it is not the case that more quay cranes should be assigned to the ship with larger workloads. The shipping date of vessels has to be taken into consideration. If a ship can stay in the port for a very long period of time, quay cranes should be scheduled to other ships with shorter shipping date which can avoid dispatching charge from the increase in operational cost.

- Quay cranes are assigned according to density distribution of containers

If distribution of containers to be handled is relatively intensive, for example, two bays are involved in operational process. In spite of large workloads, only one quay crane can be assigned considering the volume and width of quay cranes

- Quay cranes are allocated according to dispatching fees of vessels

If there are too many berthing ships and relatively few quay cranes can be assigned to operate tasks, quay cranes must be allocated to the vessel with most expensive dispatching charge, thus minimizing operational cost in container terminals.

THE MODEL

In this section, a mixed integer programming model is proposed which is a representation of the daily stowage planning forexport containers.

Notations:

v = The vessel v waiting for allocation.

q/m = The quay crane q/m.

t_v = Which means loading and unloading tasks of vessel v. It is expressed bymove and *hook* in logistic term.

S_v = Which means available operating time of vessel v, also known as the shipping date.

P_v = Which shows the berthing order of the vessel v. All containers are arranged from left to right according to berthing position.

F_v = Which means dispatching fee of vessel v under the agreement between ship-owning company and the terminal.

μ_v = Which means maximum number of available operations.

Z_q = A binary number employed to describe the status of quay crane q. 1, quay crane is in normal condition; 0, otherwise.

A_q = Handling capability of quay crane q, namely, estimated hourly quantity of each crane.

R_{mq} = A binary number which describes position order of quay crane m and quay crane q. 1, quay crane m is on the right side of quay crane q; 0, otherwise.

X_{qv} = Decision variable of the model; a binary number used to express whether quay crane q is assigned to vessel v.

Constraints

Constraints 1: Non-interference principle: Considering operational differences in efficiency and status between quay cranes, scheduling objects should be specified. As quay cranes are rail-mounted and share same rail, the position order cannot be changed. Neighboring quay cranes are not allowed to take tasks as shown in Fig.1, that is, the left crane is assigned to ship on the right side while right crane is scheduled to serve ship on the left side which can be expressed as follow:

$$\sum_v (X_{qv} \cdot p_v) \le \sum_m (\sum_v (X_{mv} \cdot p_v) \cdot r_{mq}) \ \forall q \tag{1}$$

On the left side of this equation, two-dimensional matrix of q and v is obtained by $X_{qv}.p_v$ and then:

$$\sum_v (X_{qv} \cdot p_v)$$

is the summation of $X_{qv}.p_v$ with respect to v, namely, the result is the serial number of ship in correspondence with quay crane q.

On the right side of this equation, ship's serial number in relation with quay crane m is expressed by:

$$\sum_v (X_{mv} \cdot p_v)$$

after its multiplication with r_{mq}, a two-dimensional matrix is generated. In the matrix, the positive number represents ship's serial number that allocated to quay crane m which is on the right side of q. After summation with respect to m, sequence number of certain vessel is obtained in accordance with adjacent quay crane on the right side of q.

In order to satisfy non-interference principle of quay crane allocation, the left side of equation is not larger than right side. Serial number of the ship as to quay crane q is smaller than that number in relation with quay cranes on the right side of q.

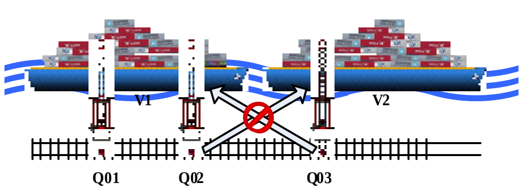

Fig. 1: Constraint 1

Constraints 2: Uniqueness principle: This constraint guaranteesthat one quay crane can only be assigned to one vessel. As shown in Fig. 2, when Q02 has already been scheduled to V1 it won't be scheduled to V2 later on. The expression can be described as follow:

$$\sum_v X_{qv} = 1 \ \forall q \tag{2}$$

Constraints 3: Maximum number of available operations for each vessel: As shown in Fig.3, during loading or unloading process, when a ship is served by two quay cranes, the distance between them should be as long as a big bay due to the width of quay crane. And as a result, the number of quay cranes for each ship cannot be more than maximum number of available operations:

$$\sum_q X_{qv} \cdot z_q \le u_v \ \forall v \tag{3}$$

The number of quay cranes for each ship is obtained from the left side of equation and U_v on the right side is maximum number of available operations for each vessel. And so, the left one shouldn't be bigger than right one, making restriction on number of quay cranes assigned to each ship.

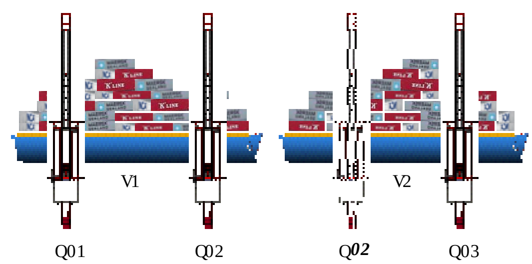

Fig. 2: Constraint 2

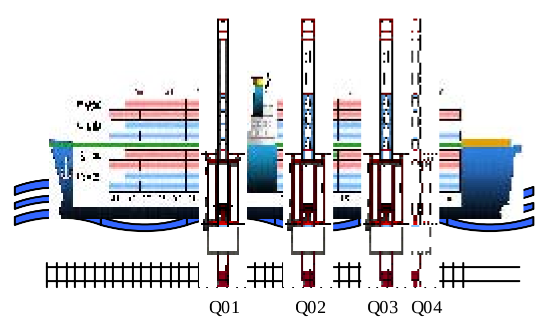

Fig. 3: Constraint 3

Objective

Objective 1: Minimizing loss of delay in shipping date: When assigning quay cranes according to the requirement of handling workloads and shipping date of various ships, if the requirement of all ships can't be satisfied, the dispatching penalty triggered by delay in shipping date should be minimized:

$$\mathrm{Obj1} = \sum_v \begin{cases} (f_v + 1) & t_v / s_v > \sum_q (X_{qv} \cdot a_q \cdot z_q) \\ 0 & t_v / s_v \le \sum_q (X_{qv} \cdot a_q \cdot z_q) \end{cases} \tag{4}$$

In the above equation:

$$t_v / s_v \ > \text{or} \le \ \sum_q (X_{qv} \cdot a_q \cdot z_q)$$

is employed to explain if vessel v is delayed. Amongst, T_v/S_v is required quantity of tasks per unit time for vessel v:

$$\sum_q (X_{qv} \cdot a_q \cdot z_q)$$

shows the working quantity of quay cranes that are actually assigned to vessel v. So this objective is used to demonstrate total dispatching penalty and number of delayed ships.

Objective 2: The principle of uniform distribution: There exists limitation when only objective 1 is met. The result of experiments of solution for model may be described as follows: Due to large workloads of V1, even if maximum available operations are provided, the tasks cannot be finished within shipping date. At this time, this specific vessel is neglected and quay cranes are scheduled to other ships, as shown in Fig. 4.

As a matter of fact, quay-crane allocation can be defined as the distribution of handling capacity, the principle of uniform distribution contains two aspects of meanings. On the one hand, when delay of vessel *v* is inevitable because of insufficient handling capability, surplus cranes should be allocated to delayed ship. On the other hand, since there are no delayed ships, remaining handling capability abides by equilibrium assignment as far as possible. The objective can be expressed by the following equation:

$$\mathrm{Obj2} = \sum_v \left[\sum_q \left(X_{qv} \cdot a_q \cdot z_q \right) - t_v / s_v \right]^2 \tag{5}$$

One-dimensional matrix as to vessel *v* is obtained from:

$$\sum_q \left(X_{qv} \cdot a_q \cdot z_q \right) - t_v / s_v$$

and surplus handling capacity allocated to vessel v is illustrated by this matrix. The positive margin explains that the number of assigned quay cranes is more than ship's demand while negative one accounts for that the shipping date cannot be guaranteed. According to uniform distribution, absolute value of surplus is supposed to be minimized and degree of demand assignment is measured by squared value of this margin.

The overall objective can be integrated as follow:

$$T\_obj = a * \mathrm{Obj1} + b * \mathrm{Obj2} \tag{6}$$

Herein, a and c are weighting coefficients of the objective function which represent the importance of a certain objective.

NUMERICAL EXPERIMENTS

In this section, the proposed quay crane allocation problem is evaluated using practical data generated from a typicalcontainer terminal. The solution approach is run on a personal computer with duo CPU @ 1.8 GHz and 1 GB RAM. And the mathematical programming model is solved using CPLEX 10.0, a commercial software package. The initial data are summarized in Table 1 and 2.

It can be observed from the Table 3 and Fig. 5 that three vessels are planned to conduct the handling

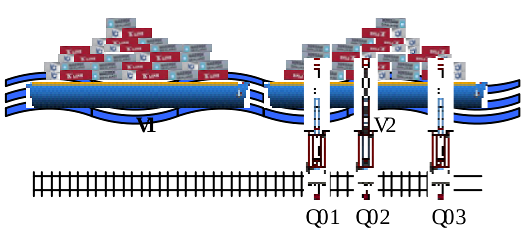

Fig. 4: Diagram of non-uniform quay-crane allocation

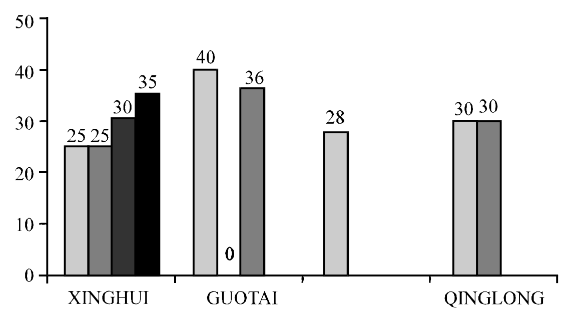

Fig. 5: Comparison of handling workloads

Table 1:Information of the vessels

Name	Tasks	Time	Sequence	Max QC no
XINHUI	228	2.5	1	4
GUOTAI	85	2	2	4
YONGHUA	260	4	3	3
QINGLONG	140	3	4	5

Table 2:Information about quay cranes

QC	Tasks	Ability
Q01	1	25
Q02	1	25
Q03	1	30
Q04	1	35
Q05	1	40
Q06	0	40
Q07	1	36
Q08	1	28
Q09	1	30
Q10	1	30

Table 3:Computational results

vQ	XINHUI	GUOTAI	YONGHUA	QINGLONG
Q1	1	0	0	0
Q2	1	0	0	0
Q3	1	0	0	0
Q4	1	0	0	0
Q5	0	1	0	0
Q6	0	1	0	0
Q7	0	1	0	0
Q8	0	0	1	0
Q9	0	0	0	1
Q10	0	0	0	1
	Complete	Complete	Delay	Complete

workloads while the departure of the vessel'YONGHUA' may be delayed.

CONCLUSION

Container terminal plays an important role in the container transportation. High-quality and efficient operational management not only meets with requirement of terminal's development but also the demand from shipping companies and cargo owners. This study sums up quay-crane allocation and scheduling experience in several container terminals and quay-crane allocation model is established based on advance rule, providing new ideas about operational optimization and strategic decision of handling processes. According to such key factors as workloads, shipping date, density distribution of containers and scheduling fees, quay cranes are allocated evenly to each vessel for the pursuit of high-efficiency operation with lowest cost. Through validation of the data, quay-crane scheduling optimization problem can be well solved. Application of this model helps to improve productivity and equipment utilization in container terminals, thus upgrading its international competitiveness and bringing about practicality for port management and control.

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