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Addressing a Coordinated Quay Crane Scheduling and Assignment Problem by Red Deer Algorithm

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ABSTRACT

Nowadays, there is much atten [illegible] of container terminals in the global trade centers. The high cost of quay cranes m [illegible] and industrial practitioners especially in the last decade to develop novel optim [illegible] mod [illegible] ess this dilemma. This study proposes a coordinated optimization model to cover both Qu [illegible] heduling Problem (QCSP) and Quay Crane Assignment Problem (QCAP) as among the first [illegible] this area. Another main contribution of this paper is to apply a recent nature-inspired algo [illegible] Red Deer Algorithm (RDA). The RDA revealed its performance for a variety of combin [illegible] mization problems in different real-world applications. This is the first attempt in the lite [illegible] nploy this recent metaheuristic to solve the proposed Coordinated Quay Crane Scheduli [illegible] signment Problem (CQCSAP). Finally, an extensive comparison discussion is considered [illegible] e main benefits of the proposed optimization model and solution algorithm.

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1. INTRODUCTION AND LITERATURE REVIEW

Academically, the container terminals were established in the late 1960s to accommodate container ships traveling between Europing contries and the United States [1, 2]. In order to reduce the traveling costs, shippers are always looking for more economical size of containers, building larger vessels for long journeys, and improve facilities and technology for servicing ships [3].

Due to the high cost of establishing berths and their equipment, the main focus is on optimizing the activities of berths and their equipment, such as Quay Cranes (QCs). The first problem for a terminal is to assign a berth location and the time of service to the vessel. The second problem is to assign the quay cranes to the ships [4]. Therefore, the objective is to optimal allocation of the cranes to the vessel. The third problem is the scheduling of the quay cranes, which determines the sequence of each crane processing to minimize loading/unloading time of the ship. Considering that QC Assignment Problem (QCAP) and QC Schduling Problem (QCSP) have many similarities. They have been combined over and over again, which increases the efficiency of the seaside operations. The assignment of QCs is effective in determining the sequences of QCs, hence in integrating QCSP and QCAP, the quay cranes would become more efficient [5].

The problem of the quay scheduling was first introduced by Daganzo [6] in 1989. He presented an MIP model aimed at reducing the costs of delayed ship loading and solved the problem by exact and approximate solution methods. Later in 2004, Kim and Park [7] studied scheduling problem of quay cranes which are the most important equipment on the terminals. In 2008, Imai et al. [8] examined the effectiveness of the QCSP and QCAP in a multi-user container terminal. Goodchild and Daganzo [9] reviewed the long-term impact of double cycling on berth equipment, such as cranes and the usefulness of the quay.

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Based on the recent advances in this research area, in 2017, Wu and Ma [10] focused on the problem of scheduling quay cranes, by considering the draft and trim constraints, with the goal of minimizing loading time. In 2018, Agra and Oliveira [11] presented an integrated model of berth allocation, quay crane assignment and scheduling problem, considering a set of heterogeneous cranes with discretion for time and space variables. The efficient operation of the terminal depends on the proper planning of the container movement, called "stowage planning". Recently, Azevedo [12] addressed the integrated problem of the 3D stowage planning problem and quay cranes scheduling problem in container vessels. More recently, an integrated berth allocation and quay crane assignment and scheudling was developed by Kasam and diabet [13]. They considered a case study in United Arabia Emarates to validate the proposed model. At the last but not the least, Correcher et al. [14] developed some exact methods to address a berth allocation problem and quay crane assignment scheduling.

In this study, the fixed costs include the cost of closing contract and the cost of assigning cranes. The variable costs incurred by the port include the cost of moving cranes between the ships bays and the cost of the processing time of each crane on board. These limitations motivate our attempts to propose a Coordinated Quay Crane Scheduling and Assignment Problem (CQCSAP) for the first time in the literature. Another main contribution of this research is to apply a recent nature-inspired algorithm, namely, Red Deer Algorithm (RDA) for the first time in the literature.

The rest of the paper is organized as follows. Section 2, addresses the proposed problem along with main assumptions and formulation. Section 3, the introduced RDA along with its encoding scheme are explained. Computational results are investigated in section 4. Finally, discussion and suggestions for the future works are investigated in section 5.

2. PROBLEM DESCRIPTION AND MODLING

Since all cranes move on one rail, it is important to keep in mind that the cranes do not physically collide with each other. To prevent collisions, the cranes are indexed in an ascending order from left to right. Cranes with a smaller index should not be placed in the right side of the cranes with a higher index. This can be seen in Figure 1. For example, if QC1 of the first contractor is assigned to the second bay of the first ship, QC2 of the first contractor cannot be assigned to the first bay of the first ship, as it leads to interference of the cranes.

The proposed optimization model is based on the following assumptions:

- Each vessel is partitioned into several bays.
- Each vessel is assigned to a maximum of one contractor for servicing.
- Each ship bay is allocated to a maximum of one crane for loading/unloading.
- The crane activity can be loading or unloading.
- Consider multiple contractors for assigning to vessels.
- Each contractor runs and operates several quay cranes
- The performance rate of each contractor's cranes is varying with another contractor's cranes.
- Consider soft time window to serve each ship.
- Pre-emption is considered by this study.
- Cranes can move freely to the left and right (Bidirectional is allowed).
- Several times are considered.
- The cost of moving cranes between ship bays is considered.
- Creating balance in the number of remaining containers on every ship's bay is considered.

We define the indexes, parameters and decision variables as follows:

Sets

M	number of vessels $(m=1,2,\ldots,M)$
Q	number of contactors $(q=1,2,\ldots,Q)$
T	number of planning period $(t=1,2,\ldots,T)$
J_m	number of bays of vessel m $(j=1,2,\ldots,J_m)$
I_q	number of quay crane of contractor q

Parameters

μ_q	the identical rate of operation for contractor q
ω_{jm}	workload in containers at bay j of vessel m to be handled

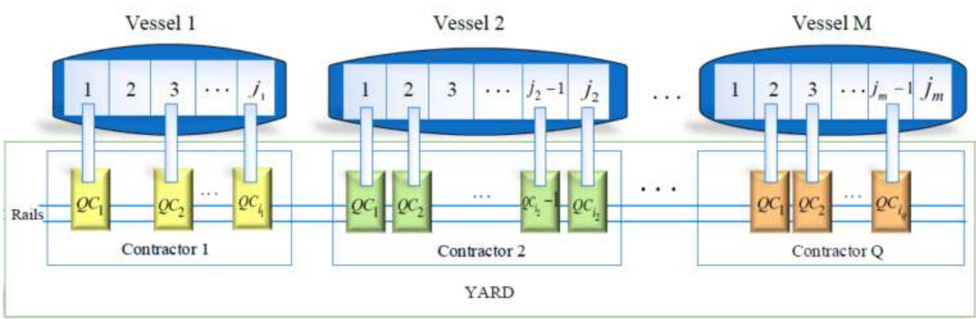

Figure 1. Graphical illustration of proposed problem with several contractors and vessels

D_m	due date of vessel m
R_m	tardiness cost of vessel m
R'_m	earliness income of vessel m
C	the cost of difference between the workload remaining for every bays of vessels
C'	fixed cost of using (allocating) the QC
C''_{qm}	fixed cost of using (allocating) the contractor q-th contractor to m-th vessel
$\lambda_{ijj'qm}$	travel cost of the i-th QC of Q-th contractor from j-th bay to j'-th bay from vessel m
I_m	variable cost of using QC on vessel m
M	A large number

Variables

x^t_{ijqm}	A binary decision variable which is 1 if i-th QC of q-th contractor is assigned to j-th bay of vessel m at time t, and 0 otherwise
w^t_{jm}	the unhandled workload at time t in j-th bay of m-th vessel
$w'^t_{jj'm}$	the difference between the workload existing in bay j and bay j' of vessel m at time t
Z_{qm}	A binary decision variable which is 1 if Q-th contractor is assigned to m-th vessel, and 0 otherwise
$y^t_{ijj'qm}$	A binary decision variable which is 1 if i-th QC of q-th contractor is moved from bay j to bay j' of vessel m at time t, and 0 otherwise
T_{jmt}	A binary decision variable which is 1 if bay j of vessel m is handled at time t, and 0 otherwise
v^t_{jm}	level of inventory at time t in j-th bay of m-th vessel
α^t_{jm}	A binary decision variable which is 1 if level of inventory in j-th bay of m-th vessel at time t is positive, and 0 otherwise
T'_m	completion time of vessel m
F_m	tardiness of vessel m
E_m	earliness of vessel m

$$\begin{aligned}\min \sum_m^M\sum_j^{J_m}\sum_{j'}^{J_m}\sum_t^T C.\left|w^t_{jm}-w^t_{j'm}\right| + \sum_m^M\sum_q^Q\sum_i^{I_q}\sum_j^{J_m}\sum_t^T C' t x^t_{ijqm} + \sum_q^Q\sum_m^M C''_{qm}Z_{qm} \\ + \sum_m^M\sum_q^Q\sum_i^{I_q}\sum_j^{J_m}\sum_{j'}^{J_m}\sum_t^T \lambda_{ijj'qm}y^t_{ijj'qm} + \sum_m F_m R_m - \sum_m E_m R'_m + \sum_m I_m T'_m\end{aligned} \quad (1)$$

In this model, the objective function (1) in all vessels minimizes the sum of difference in the remaining workload on both bays of the ship, in addition, it prevents the allocation of cranes to ship bays in the subsequent periods. It also minimizes the costs related to assigning the contractor, displacing the cranes between bays, deviating from due date and processing (loading or unloading) on each vessel, while also maximizing the profit from earliness. Since the objective function is nonlinear, it is converted to a linear relation with the aid of Equations (30), (31), (32) and (33), which will be explained in more detail.

$$\sum_{m=1}^{M}\sum_{j=1}^{J_m} x^t_{ijqm} \le 1 \qquad \forall q=1,...,Q \, \forall i=1,...,I_q, \forall t=1,...,T \quad (2)$$

$$\sum_{q=1}^{Q}\sum_{i=1}^{I_q} x^t_{ijqm} \le 1 \qquad \forall j=1,...,J_m, \forall t=1,...,T, \forall m=1,...,M \quad (3)$$

$$\sum_{t=1}^{T}\sum_{q=1}^{Q}\sum_{i=1}^{I_q} \mu_q x^t_{ijqm} \ge \omega_{jm} \qquad \forall j=1,...,J_m, \forall m=1,...,M \quad (4)$$

$$v^1_{jm} = \omega_{jm} - \sum_{i=1}^{I_q}\sum_{q=1}^{Q} \mu_q x^1_{ijqm} \qquad \forall j=1,...,J_m, \forall m=1,...,M \quad (5)$$

$$v^t_{jm} = v^{t-1}_{jm} - \sum_{i=1}^{I_q}\sum_{q=1}^{Q} \mu_q x^t_{ijqm} \qquad \forall j=1,...,J_m, \forall m=1,...,M, \forall t=2,...,T \quad (6)$$

$$v^t_{jm} \le M\alpha^t_{jm} \qquad \forall j=1,...,J_m, \forall m=1,...,M, \forall t=1,...,T \quad (7)$$

$$v^t_{jm} \ge -M\left(1-\alpha^t_{jm}\right) \qquad \forall j=1,...,J_m, \forall m=1,...,M, \forall t=1,...,T \quad (8)$$

$$w^t_{jm} \le v^t_{jm} + M\left(1-\alpha^t_{jm}\right) \qquad \forall j=1,...,J_m, \forall m=1,...,M, \forall t=1,...,T \quad (9)$$

$$w^t_{jm} \ge v^t_{jm} - M\left(1-\alpha^t_{jm}\right) \qquad \forall j=1,...,J_m, \forall m=1,...,M, \forall t=1,...,T \quad (10)$$

$$w^t_{jm} \le \alpha^t_{jm} M \qquad \forall j=1,...,J_m, \forall m=1,...,M, \forall t=1,...,T \quad (11)$$

$$\sum_{i'=i+1}^{I_q}\sum_{j'=1}^{J_m-1} x^t_{i'j'qm} \le M(1-x^t_{ijqm}) \qquad \forall q=1,...,Q, \forall i=1,...,I_q, \forall j=1,...,J_m, \forall t=1,...,T, \forall m=1,...,M \quad (12)$$

$$\sum_{q'=q+1}^{Q}\sum_{m'=1}^{m-1} Z_{q'm'} \le M(1-Z_{qm}) \qquad \forall m=1,...,M, \forall q=1,...,Q-1 \quad (13)$$

$$\sum_{j=1}^{J_m}\sum_{i=1}^{I_q}\sum_{t=1}^{T} x^t_{ijqm} \le Z_{qm}.M \qquad \forall q=1,...,Q, \forall m=1,...,M \quad (14)$$

$$\sum_{m=1}^{M} Z_{qm} \le 1 \qquad \forall q=1,...,Q \quad (15)$$

$$\sum_{q=1}^{Q} Z_{qm} = 1 \qquad \forall m=1,...,M \quad (16)$$

$$\sum_{q=1}^{Q}\sum_{i=1}^{I_q} x^1_{ijqm} = T_{jm1} \qquad \forall j=1,...,J_m, \forall m=1,...,M \quad (17)$$

$$\sum_{q=1}^{Q}\sum_{i=1}^{I_q} x^t_{ijqm} - M.\sum_{\tau=1}^{T-1} T_{jm\tau} \le T_{jmt} \qquad \forall j=1,...,J_m, \forall m=1,...,M, \forall t=1,...,T \quad (18)$$

$$T'_m \ge T_{jmt}.t \qquad \forall m=1,...,M, \forall j=1,...,J_m, t=1,...,T \quad (19)$$

$$E_m - F_m = D_m - T'_m \qquad \forall m = 1,\ldots,M \tag{20}$$

$$y^t_{ijj'qm} \geq x^t_{ijqm} + x^{t+1}_{ij'qm} - 1 \qquad \forall i=1,\ldots,I_q, \forall j=1,\ldots,J_m, \forall j'=1,\ldots,J_m, j \neq j', \forall q=1,\ldots,Q, \forall m=1,\ldots,M, \forall t=1,\ldots,T-1 \tag{21}$$

$$x^t_{ijqm} \in \{0,1\} \qquad \forall i=1,\ldots,I_q, \forall j=1,\ldots,J_m, \forall q=1,\ldots,Q, \forall m=1,\ldots,M, \forall t=1,\ldots,T \tag{22}$$

$$w^t_{jm} \geq 0 \qquad \forall j=1,\ldots,J_m, \forall m=1,\ldots,M, \forall t=1,\ldots,T \tag{23}$$

$$E_m, F_m, T'_m \geq 0 \qquad \forall m=1,\ldots,M \tag{24}$$

$$Z_{qm} \in \{0,1\} \qquad \forall q=1,\ldots,Q, \forall m=1,\ldots,M \tag{25}$$

$$y^t_{ijj'qm} \in \{0,1\} \qquad \forall i=1,\ldots,I_q, \forall j=1,\ldots,J_m, \forall j'=1,\ldots,J_m, \forall q=1,\ldots,Q, \forall m=1,\ldots,M \tag{26}$$

$$T_{mjt} \in \{0,1\} \qquad \forall m=1,\ldots,M, \forall j=1,\ldots,J_m, \forall t=1,\ldots,T \tag{27}$$

$$\alpha^t_{jm} \in \{0,1\} \qquad \forall m=1,\ldots,M, \forall j=1,\ldots,J_m, \forall t=1,\ldots,T \tag{28}$$

$$v^t_{jm} \in free \qquad \forall m=1,\ldots,M, \forall j=1,\ldots,J_m, \forall t=1,\ldots,T \tag{29}$$

Constraint (2) shows that each crane of each contractor is assigned at any time to a maximum of one ship bay. Constraint (3) shows that each ship bay can be serviced by at most one crane of one contractor at any given time. Constraint (4) ensures that the number of cranes assigned to each bay is sufficient to complete the operation on that bay. With the help of constraints (5) and (6), the inventory level of ships bays is calculated for all time periods. By using constraints (7) and (8), if the inventory level is positive, $(v^t_{jm} > 0)$, the constraint (8) is deactivated and α^t_{jm} is equal to 1, and if $v^t_{jm} < 0$, the constraint (7) is deactivated and α^t_{jm} is equal to 0. The constraints (9), (10), and (11) determine the relationships between variables, α^t_{jm}, v^t_{jm}, and w^t_{jm}. If $\alpha^t_{jm} = 1$, the variables v^t_{jm}, w^t_{jm} are the same and if $\alpha^t_{jm} = 0$, then $w^t_{jm} = 0$. Constraint (12) prevents the cranes interference in allocation to the ships bays. The indexing of ship bays and cranes is arranged in ascending order based on their position, so that, it is not allowed to place a high index crane on the left side of lower index crane. Constraint (13) prevents interference of contractors with their ship assignments. Similar to the constraint (12), the indexing of contractors and ships is arranged in ascending order according to their position. Constraint (14) indicates that if the contractor *q* is not assigned to the vessel *m*, there is no possibility of assigning cranes of contractor *q* to the vessel *m*, and if the contractor *q* is assigned to the vessel *m*, the cranes of the contractor *q* can be assigned to the vessel *m*. Constraint (15) indicates that each contractor can be assigned to at most one vessel, and constraint (16) ensures that each vessel is assigned exactly to one contractor for servicing. Constraints (17) and (18) compute the completion time of each bay. Because the service to any vessel ends when the loading/unloading of all bays of that vessel is completed, the constraint (19) calculates the completion time of each ship. With obtaining the completion time of the vessel and calculating the time difference with the due date constraint (20) determines the tardiness or earliness of each ship. Constraint (21) determines the movements carried out by each crane of a contractor. Constraints (22) to (29) determine the range of decision variables.

In order to linearize the objective function, we rewrite the objective function (1) as (30) and add constraints (31) to (33) to it.

$$\begin{aligned} \min & \sum_{m}^{M}\sum_{j}^{J_m}\sum_{j'}^{J_m}\sum_{t}^{T} C.w'^{t}_{jj'm} + \sum_{m}^{M}\sum_{q}^{Q}\sum_{i}^{I_q}\sum_{j}^{J_m}\sum_{t}^{T} C' t x^t_{ijqm} + \sum_{q}^{Q}\sum_{m}^{M} C''_{qm} Z_{qm} \\ & + \sum_{m}^{M}\sum_{q}^{Q}\sum_{i}^{I_q}\sum_{j}^{J_m}\sum_{j'}^{J_m}\sum_{t}^{T} \lambda_{ijj'qm} y^t_{ijj'qm} + \sum_{m}^{M} F_m R_m + \sum_{m}^{M} E_m R'_m + \sum_{m}^{M} I_m T'_m \end{aligned} \tag{30}$$

$$w'^{t}_{jj'm} \geq w^t_{jm} - w^t_{j'm} \qquad \forall j=1,\ldots,J_m, \forall j'=1,\ldots,J_m, \forall m=1,\ldots,M, \forall t=1,\ldots,T \tag{31}$$

$$w'^{t}_{jj'm} \geq w^t_{j'm} - w^t_{jm} \qquad \forall j=1,\ldots,J_m, \forall j'=1,\ldots,J_m, \forall m=1,\ldots,M, \forall t=1,\ldots,T \tag{32}$$

$${}^{t}_{j'm} \geq 0 \qquad \forall j=1,\ldots,J_m, \forall j'=1,\ldots,J_m, \forall m=1,\ldots,M, \forall t=1,\ldots,T \tag{33}$$

3. RED DEER ALGORITHM (RDA)

This is the first attempt to employ the Red Deer Algorithm (RDA) firstly introduced by Fathollahi Fard and Hajiaghaei-Keshteli [15] to solve the proposed CQCSAP. Similar to other metaheuristics, the RDA generates a random population divided into two types: "male RDs" as the best solutions and "hinds" as the rest of solutions. Generally, roaring, fighting and mating are three main behaviours of RDs during the breeding season [16]. During this competition, the better solutions as the winners chosen again as the commanders to form the harems, which are a group of hinds. First, the commanders should mate with a number of hinds in the harem and a few ones in another harem to extent his territory. The stags can mate with the nearest hind without the limitation of harems [16]. Regarding the evolutionary concepts in the RDA, a set of better solutions will be chosen as the next generation of algorithm by roulette wheel selection or tournament selection mechanisms. At the end, the stop condition of this algorithm based on the maximum number of iterations should be satisfied. More details about this algorithm is referred to literature [15, 17].

3. 1. Encoding Scheme

Whenever a metaheuristic procedure is used, coding and decoding the solution of mathematical problem is required [18-21]. Due to page limitation, the encoding scheme is refferd to the literature [12-14].

4. COMPUTATIONAL EXPERIMENTS

In this section, the performance of the CQCSAP model is presented, then the RDA developed is verified through 8 numerical instances in small and large sizes. The range of parameters are bechmaked from Agra and Oliveira [20]. Because of the number of $\lambda_{ijj'qm}$ values is very high and it is not possible to demonstrate them in this study, the value of $\lambda_{ijj'qm}$ for all vessel, bays, contractors and cranes are considered to be 1 in order to easily display the values of this parameter. Note that each test problem is solved for 20 times by the RDA. To approve the quality of RDA statistically, we have employed Genetic Algorithm (GA) as already applied succesfuly in the literature based on statistical analyses shown in Figure 2. This indicates the performance of RDA compared with GA.

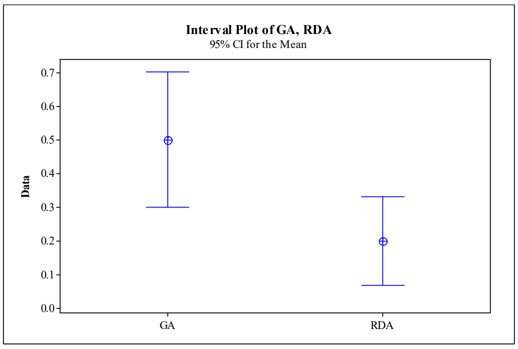

Figure 2. Statistical analyses based on interval plots for RDA and GA

5. CONCLUSIONS

In this research, a Coordinated Quary Crane Scheduling and Assignment Problem (QCAP) was addressed by the Red Deer Algorithm (RDA). To verify the accuracy and verification of the proposed model and the RDA performance, some instances were solved and compared with GA statistically. The results show the high-efficiency of proposed RDA.

For future works, more in-depth analyses and sensitivities can be ordered for the proposed model. Other metaheuristics can be utilized to address the proposed QCAP.

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Nature-inspired Algorithm
Red Deer Algorithm

چکیده

امروزه، توجه زیادی به برنامه ریزی ترمینال ها در بنادر در مرکز تجارت جهانی شده است. هزینه ی بالای دنده جرثقیل ها هر دوی محققان و مشارکت کنندگان امور صنعتی را به توسعه مدل های بهینه سازی به خصوص در طول دهه گذشته برای حل این معضل شوق داده است. این مطالعه در صف اولین مطالعات این حوزه به پیشنهاد یک مدل یکپارچه تخصیص و زمانبندی جرثقیل ها در بنادر را میپردازد. نوآوری دیگر این مقاله به استفاده کردن از یک الگوریتم جدید الهام گرفته از طبیعت به نام الگوریتم گوزن سرخ است. این الگوریتم موفقیت خود را در حل مسائل مختلف بهینه سازی در کاربردهای گوناگون جهان واقعی به اثبات رسانیده است. این اولین تلاش برای استفاده از این الگوریتم در این حوزه تحقیقاتی برای حل مساله یکپارچه زمانبندی و تخصیص جرثقیل ها در بنادر است. در پایان یک سری رویکردهای مدیریتی با توجه به درنظر گرفتن نقاط قوت مساله بهینه سازی پیشنهادی و روش حل مربوطه پیشنهاد شده است.

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