Journal of Marine Science and Engineering

MDPI

Supplementary File of "Enhanced Multi-Objective Evolutionary Algorithm for Green Scheduling of Heterogeneous Quay Cranes Considering Cooperative Movement and Safety"

1. Figures about EMOEA

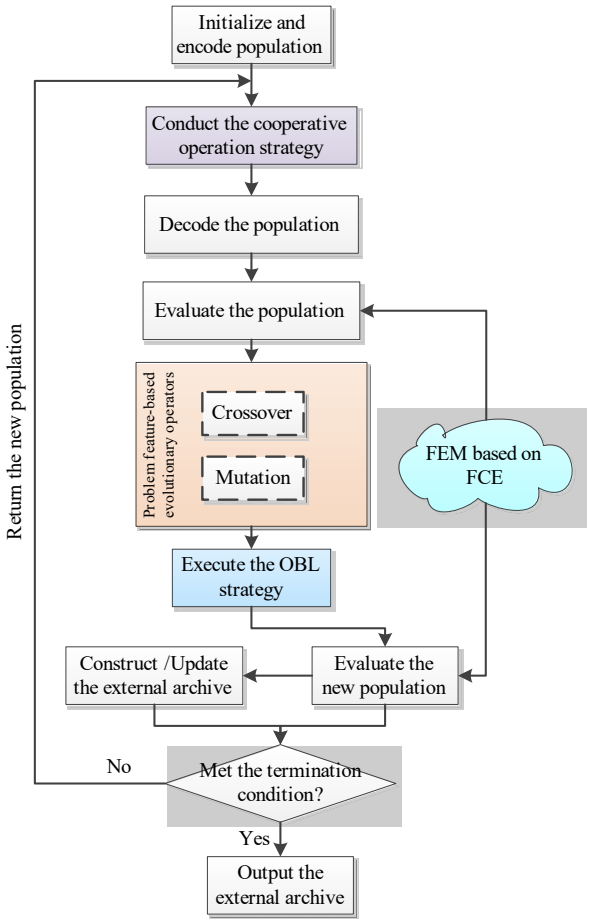

Figure S1. The framework of the EMOEA.

2. Examples

Figure S2 shows a feasible solution, the bays are divided into three parts, which is equal to the number of HQCs. The bay division A=[2,5,6], which means that the sets of bays to be operated by HQC 1, 2, and 3 are [1,2], [3,4,5] and [6], respectively. For the three HQCs, their bay arrangements are [2,1], [4,5,3] and [6], respectively. Accordingly, the bay arrangement B=[2,1,4,5,3,6]. Afterwards, the containers in each bay are randomly arranged to obtain a container operation sequence.

Figure S3 presents an example of bay division and arrangement. Suppose that h=1. Then, the bay arrangements in Figure S.3(a-c) are infeasible; they should be adjusted to be those feasible ones in Figure S.5(d-f). After this step, an infeasible solution will be a feasible one with a high probability.

Figure S4 shows an example of crossover operation for the bay division and arrangement.

Figure S5 presents an example of mutation operation for a feasible individual.

Figure S6 shows an example of the OBL for a solution.

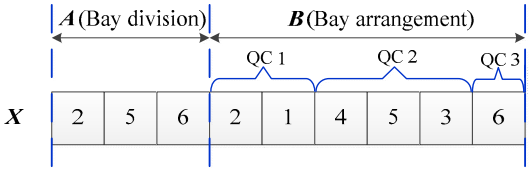

Figure S2. An example of encoding.

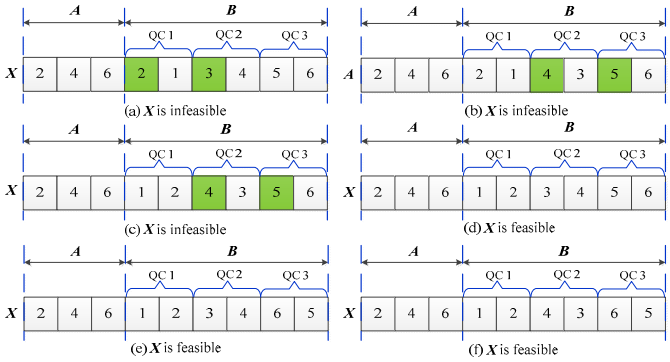

Figure S3. An example of feasible and infeasible solutions.

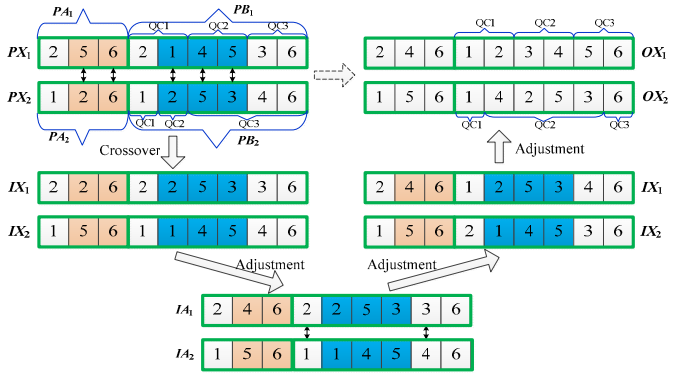

Figure S4. An example for crossover.

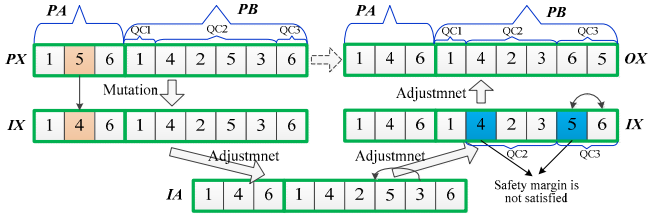

Figure S5. Mutation for bay division and arrangement part.

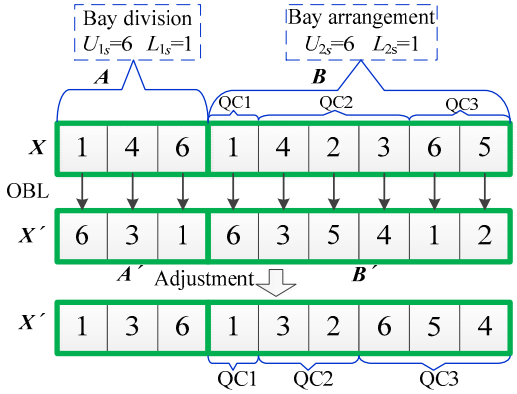

Figure S6. OBL strategy for a solution.

3. Performance metric

(1) HV is a comprehensive indicator that calculates the cumulative normalized volume covered by a solution set in relation to a given reference point. A greater HV value represents a better convergence and diversity in the solution set. HV is defined as follows:

$$HV(A,q) = volume(U_{X\in A}[f_1(X),q_1]\times\cdots\times[f_M(X),q_M]) \quad (1)$$

where A is a solution set obtained by one algorithm and $q=(q_1,q_2,\cdots,q_M)$ is the HV reference point. M is the number of objectives. In this work, as per existing studies, we set $q=(1.2,1.2,\cdots,1.2)_M$ for all the relevant algorithms.

(2) IGD is an indicator that evaluates the closeness with distribution uniformity between an obtained solution set and the true Pareto front. IGD is defined as follows:

$$IGD(A,B^*) = \frac{1}{|B^*|}\sum_{x\in B^*}\min_{y\in A} d(x,y) \quad (2)$$

where B^* means the true Pareto front and A is an obtained solution set. $d(x,y)$ is the Euclidean distance between points x and y. In this work, B^* consists of all non-dominated solutions obtained by all compared algorithms. A smaller $IGD(A,B^*)$ value represents that the A is closer to B^* and have better distribution uniformity.

(3) The *C*-metric is an indicator that reflects the dominance relationship between two solution sets *A* and *B*. *C*(*A*, *B*) represents the percentage of the solutions in *B* that are dominated by at least one in *A*. *C*(*A*, *B*) is calculated as follows:

$$C(A,B) = |\{X_2\in B|\exists X_1\in A,\ X_1 \text{ dominates } X_2\}|/|B| \quad (3)$$

where *C*(*A*, *B*)=0 means that no solution in *B* is dominated by any of the solutions in *A*, while *C*(*A*, *B*)=1 means that all solutions in *B* are dominated by solutions in *A*.

4. Parameter tuning

The proposed EMOEA has six critical parameters, including the population size *N*, the crossover probability *Pc*, the mutation probability *Pm*, the lower and upper bounds factors α and β in FCE-based FEM, and the proportion of solutions implementing OBL strategy *r*. We utilized a Taguchi analysis method to obtain the best parameter combination. We set each parameter to five levels, i.e, $N=[40,60,80,100,120]$, $Pc=[0.5,0.6,0.7,0.8,0.9]$, $P_m=[0.1,0.2,0.3,0.4,0.5]$, $\alpha=[0.2,0.4,0.6,0.8,1]$, $\beta=[1.1,1.2,1.3,1.4,1.5]$, $r=[0.1,0.2,0.3,0.4,0.5]$. Based on the HV value, the trend of each factor level is shown in Figure S. 8. According to the figure, the best parameter combination was set as follows: $N=40$, $Pc=0.7$, $Pm=0.2$, $\alpha=0.4$, $\beta=1.1$ and $r=0.4$.

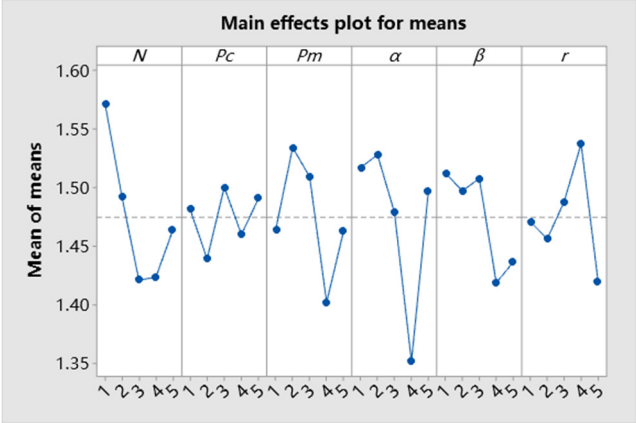

Figure S7. The trends of factor levels for key parameters.

5. The parameter configuration

Table S1 shows the parameter configuration for the EHQCCSP.

Table S1. Parameter configuration of numerical experiments

Parameter	Value	Parameter	Value
Δ	2 m	a_1	18 m
V_1^q	$U[0.5, 0.8]$ m/s	a_2	35 m
V_{21}^q, V_{22}^q	$U[3.5, 4.5]$ m/s	D	13 m
V_{31}^q	$U[2.5, 3.2]$ m/s	t_0	10 s
V_{32}^q	$U[1.2, 1.8]$ m/s	L	50 m
P_1^q	$U[2000, 2500]$KW	l_1	12.09 m
P_{21}^q, P_{22}^q	$U[100, 150]$ KW	l_2	2.35 m
P_{31}^q, P_{32}^q	$U[250, 300]$ KW	l_3	2.39 m