Supplementary materials for

Design and optimization of the collaborative container logistics system between a dry port and a water port

a

b

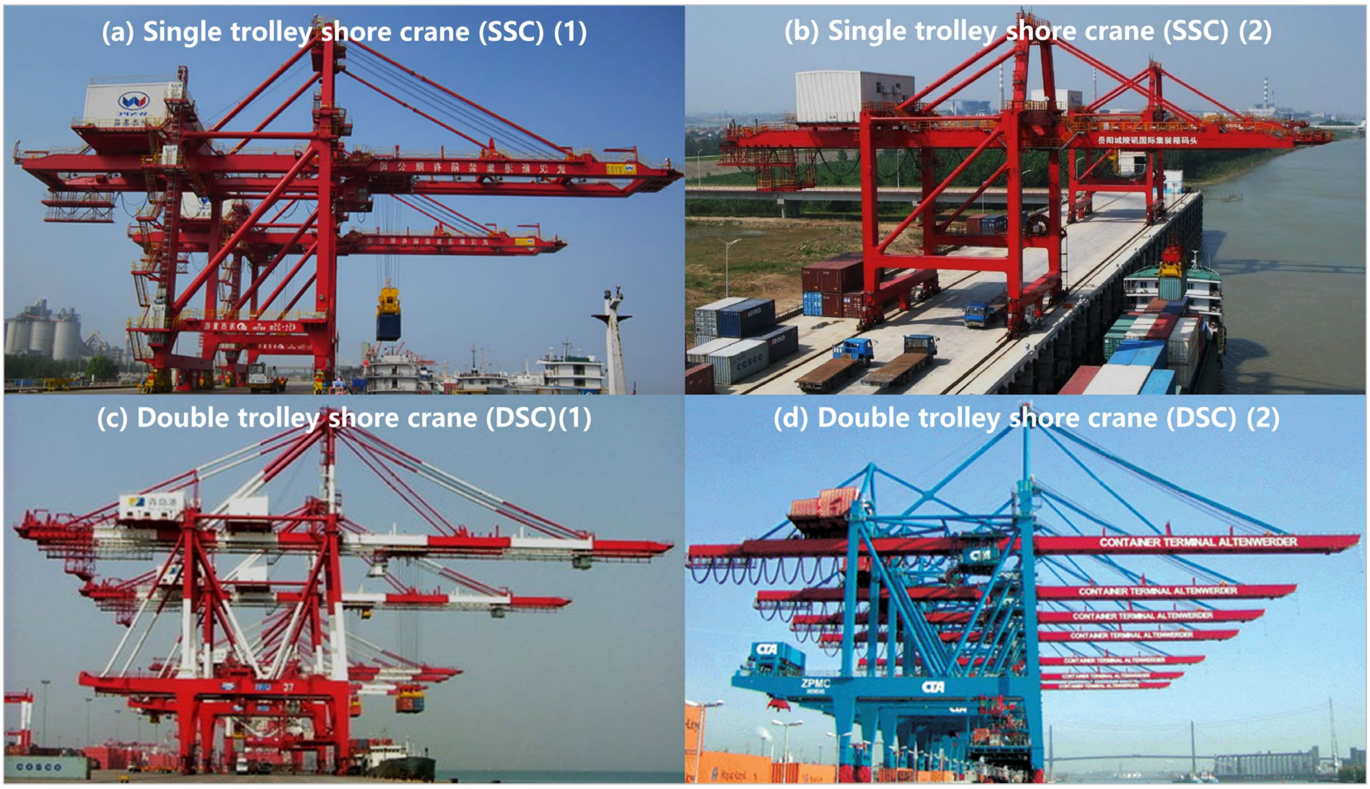
c

d

1. Elemental components of the DTDCS

1.1 Shore handling equipment

In the WP, the CCY employs the traditional single trolley shore crane (SSC) for container handling on the seaside, as shown in Annex Figure 1 and Main text Figure 9. Conversely, the SCY utilizes the double trolley shore crane (DSC) for seafront handling tasks. The main trolley of the DSC can accommodate a double spreader, while the auxiliary trolley is equipped with a single spreader. Additionally, the transfer platform can accommodate two 40-foot containers, as illustrated in Annex Figure 1 and Main text Figure 3. Both types of shoreside rail container cranes, along with subsequent yard handling equipment, are automated and can be remotely controlled by operators.



Annex Figure 1. Shore handling equipments

1.2 Yard handling equipment

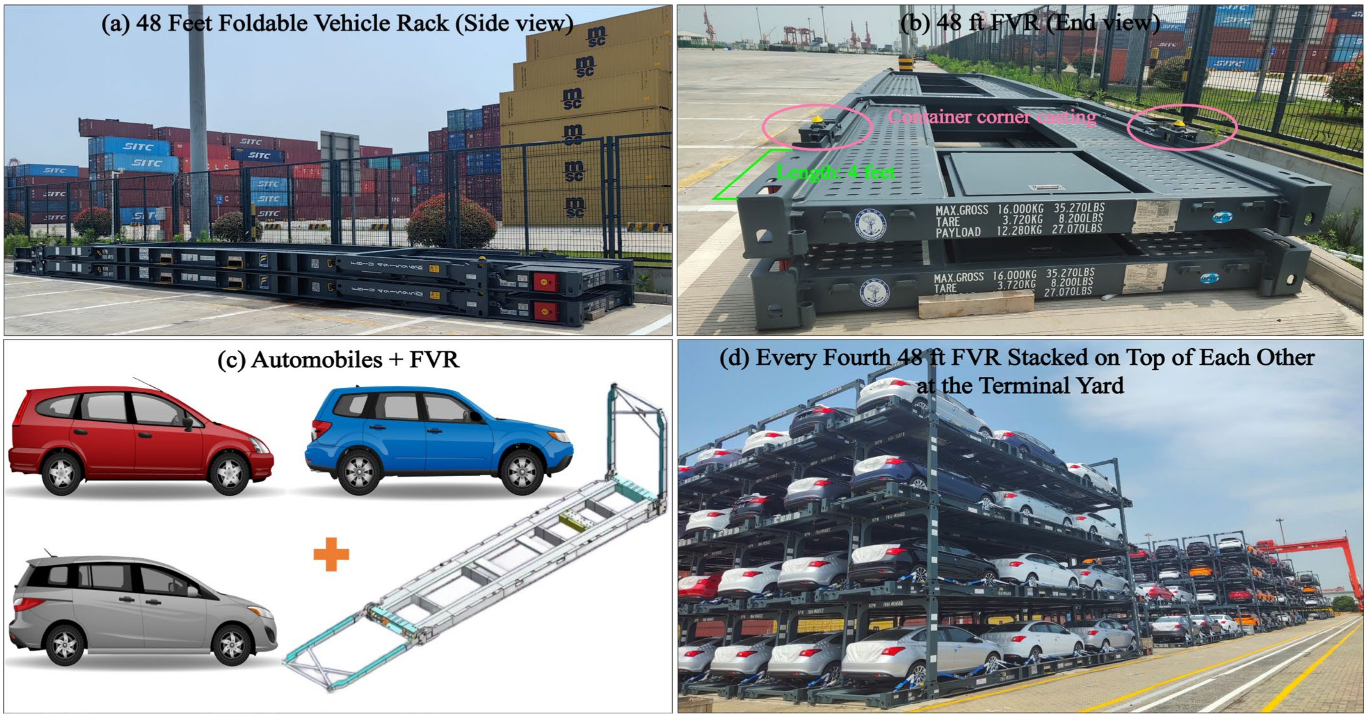
Annex Figure 2 illustrates various types of conventional yard rail cranes (CYC). In the WP, the CCY utilizes double cantilever CYC on both the sea and the land sides, while in the DP, the ICY is equipped with single-cantilever CYC on the rail side and double-cantilever CYC in internal container blocks (refer to Annex Figure 2, Main text Figure 5 and Main text Figure 9). In SCY, double-cantilever stereoscopic yard rail cranes (SYC) on the sea and land sides lift containers from the container straddle carriers (CSC) handling area to the corresponding floor of the SCY transfer platform via a lifting channel. Suspended rail cranes (SRC) on each yard floor move containers to designated bays; see Annex Figure 2 and Main text Figure 4.

Annex Figure 2. Yard handling equipments

1.3 Horizontal transport equipment

In the WP layout featuring the SCY, emphasis lies on the CSC for horizontal transportation between the quay front and SCY, as well as between the quay front and the DST handling platform. The DST handles container transport to and from the quay. In CCY and ICY operations, the CSC manages horizontal transportation between the quay front and CCY, between the CCY and DST handling platforms, and between the DST handling platforms and ICY. The DST or the outside port container truck (OCT) is responsible for container transport to or from the terminal, as illustrated in Annex Figures 3 and Main text Figure 9.

Annex Figure 3. Horizontal transport equipments



Annex Figure 4. 48-foot FVR

2. Algorithms

2.1 NSGA-II

Non-dominated Sorting Genetic Algorithm II (NSGA-II) is a classical multi-objective optimization algorithm proposed by (Deb et al., 2002). NSGA-II efficiently searches for and obtains the Pareto frontier in the multi-objective problem space, i.e., it is not possible to improve the solution set of one objective function without jeopardizing the solution sets of other objective functions. NSGA-II has four outstanding advantages:

(1) Fast convergence: NSGA-II employs non-dominated ordering and crowding degree operators, which enable the algorithm to converge to the Pareto frontiers more quickly.
(2) Efficiency: the algorithm promotes diversity and homogeneity by maintaining additional information on the crowding degree, thus improving search efficiency.
(3) Diversity: the algorithm is able to provide a wide distribution in the set of Pareto optimal solutions by maintaining diversity in the population.
(4) Adaptability: NSGA-II has adaptive parameters that enable the algorithm to solve different types of problems efficiently.

Overall, there are seven steps in the computational procedure of NSGA-II; Main text Figure 10(a) illustrates the complete flow of the algorithm.

(1) Initialisation: initialize the population and set the parameters.
(2) Non-dominated sorting: arrange individuals according to non-dominated sorting.
(3) Crowding degree calculation: calculate the crowding degree of individuals.
(4) Selection: Select the next generation of population by performing a bidding race selection operation with the results of non-dominated sorting and crowding degree calculation.
(5) Crossover and mutation: Generate new individuals by performing crossover and mutation operations on the selected individuals.
(6) Renewal of the population: Elite strategy can leave the excellent individuals in the parent generation and directly enter the offspring, and add the newly generated individuals to the new population to keep the population size unchanged.
(7) Repeat Iteration: Repeat the execution of steps 2 to 6 until the stopping condition (which can be the number of iterations or the running time) is reached.

However, since NSGA-II uses random generation in initializing the populations, the drawback of this method is that its randomness leads to uneven spatial distribution of the populations with large uncertainty. To eliminate this problem, we introduce a population improvement strategy, i.e., good point set generation of populations. The construction of the good point set is as follows:

$$\boldsymbol{P_n(i) = (r_1 i_1, r_2 i_2, r_3 i_3 \dots, r_n i_n)} \tag{24}$$

where $P_n(i)$ denotes the sample set and r refers to the good point, generally taken:

$$\boldsymbol{r = \{2\cos(2\pi i/7)\}} \tag{25}$$

Or:

$$\boldsymbol{r = \{e^i\}} \tag{26}$$

Steps for initializing the population of a good point set:

Step 1: Assume that the spatial dimension of the population is n and the number of populations is m.

Step 2: Determine r.

$$\boldsymbol{r} = (\boldsymbol{r_1}, \boldsymbol{r_2}, \boldsymbol{r_3}..., \boldsymbol{r_n}), \boldsymbol{r_j} = \boldsymbol{mod}(\mathbf{2cos}(\boldsymbol{2\pi j}/_{\boldsymbol{7}}), \mathbf{1}), \mathbf{1} \leq \mathbf{j} \leq \mathbf{n} \tag{27}$$

Step 3: Constructing the good point set.

$$\boldsymbol{P_n}(\boldsymbol{i}) = (\boldsymbol{r_1 i_1}, \boldsymbol{r_2 i_2}, \boldsymbol{r_3 i_3}..., \boldsymbol{r_n i_n}), \boldsymbol{i} = \mathbf{1}, \mathbf{2}, ..., \boldsymbol{n} \tag{28}$$

Step 4: Mapping $P_n(i)$ to the definitional domain of the population

$$\boldsymbol{X_i^j} = \boldsymbol{a_j} + \boldsymbol{P_n}(\boldsymbol{i})(\boldsymbol{b_j} - \boldsymbol{a_i}) \tag{29}$$

where a_j is the lower bound and b_i is the upper bound.

In addition, in the selection method of the parent generation, the traditional selection is the binary tournament, which randomly selects a certain number of individuals from the parent population to compete to get the offspring. However, the selection of the parent generation is close to random selection, which will affect the evolutionary speed of the whole population thus the search ability of the evolutionary process is not guaranteed. To guarantee the convergence speed of the algorithm, it is necessary to ensure the search ability in the early stage to avoid falling into the local optimum. In the later phase, it is necessary to increase the pressure on the parent selection to ensure that the algorithm converges and better approximates the true value. For this reason, we use a selection improvement strategy, that is, based on the linear ranking of the parent generation selection method. The overall realization idea is as follows.

Step 1: Sort the population individuals according to the adaptation value from smallest to largest. In NSGA-II, the rank is first sorted in descending order, and then the crowding distance is sorted in ascending order. The higher the rank (smaller the adaptation value), the higher the selection probability.

Step 2: After that, a certain linear function of interest is used to assign the probability of selection to each individual. Where x_1 is ranked highest and x_n is ranked lowest.

The individual x_i selection probability is:

$$\boldsymbol{p_i} = \mathbf{1}/_{\boldsymbol{N}}\left(\boldsymbol{\eta^-} + (\boldsymbol{\eta^+} - \boldsymbol{\eta^-})^{\boldsymbol{i}-\mathbf{1}/_{\boldsymbol{N}-\mathbf{1}}}\right) \tag{30}$$

where $i = 1,2,...,N$; η^+ and η^- are constants and $0 \leq \eta^- \leq 1$.

Step 3: According to the selection probability it is known that:

If $\eta^+ = 2$ and $\eta^- = 0$, the selection pressure of the population is maximum.

When $\eta^+ = \eta^- = 1$, then it is random selection, and the selection pressure of the population is minimum.

Step 4: To strengthen the selection pressure of the parent population in the process of calculation, add the exponential term to adjust the values of η^+ and η^- gradually with the gradual progress of the generation.

After improvement, we call the new algorithm as Improved Non-dominated Sorting Genetic Algorithm II (INSGA-II). The workflow of INSGA-II is shown in Figure 10 (a) and its pseudocode is available in Algorithm 1.

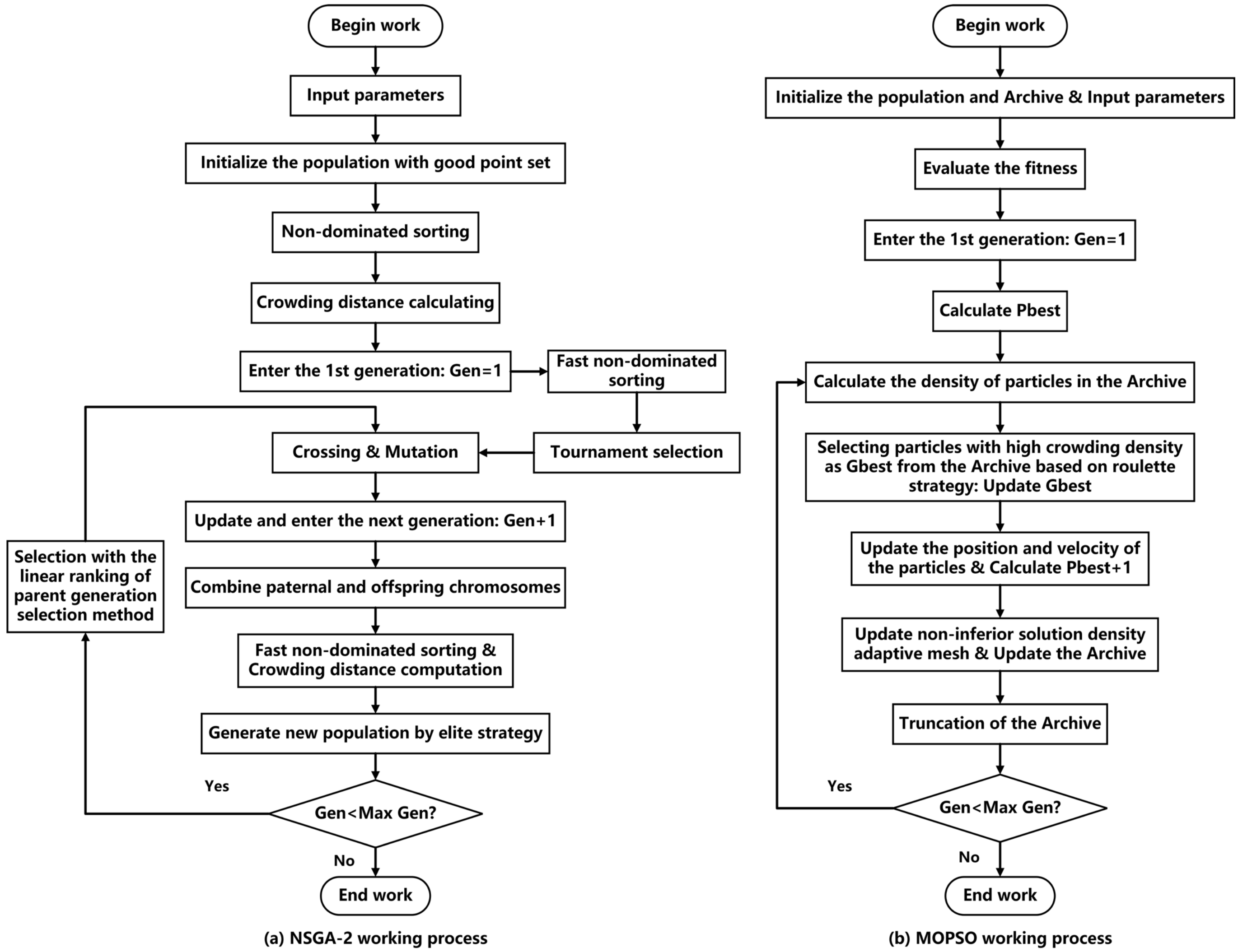
2.2 MOPSO

The Multi-objective Particle Swarm Optimization (MOPSO) algorithm was proposed by (Coello et al., 2004; Coello and Lechuga, 2002). It searches and obtains the set of Pareto frontier solutions in solving multi-objective optimization problems to provide a balanced set of solutions.The advantages of MOPSO mainly include:

(1) Fast convergence: MOPSO utilizes the idea of group intelligence to search Pareto frontiers through cooperation and information sharing of particles.
(2) Simple and easy to implement: MOPSO is based on the PSO algorithm, which is easy to understand and implement and is suitable for all kinds of multi-objective optimization problems.
(3) Adaptive: MOPSO is adaptive and can automatically adjust the parameters according to the characteristics of the problem and the objective function, which improves the robustness and applicability of the algorithm.
(4) Diversity: Because the particles maintain a certain degree of diversity during the search process, MOPSO can generate a diverse set of Pareto frontier solutions, providing more options for decision making.

MOPSO comprises six working steps, with Main text Figure 10(b) displaying the complete flow of the algorithm.

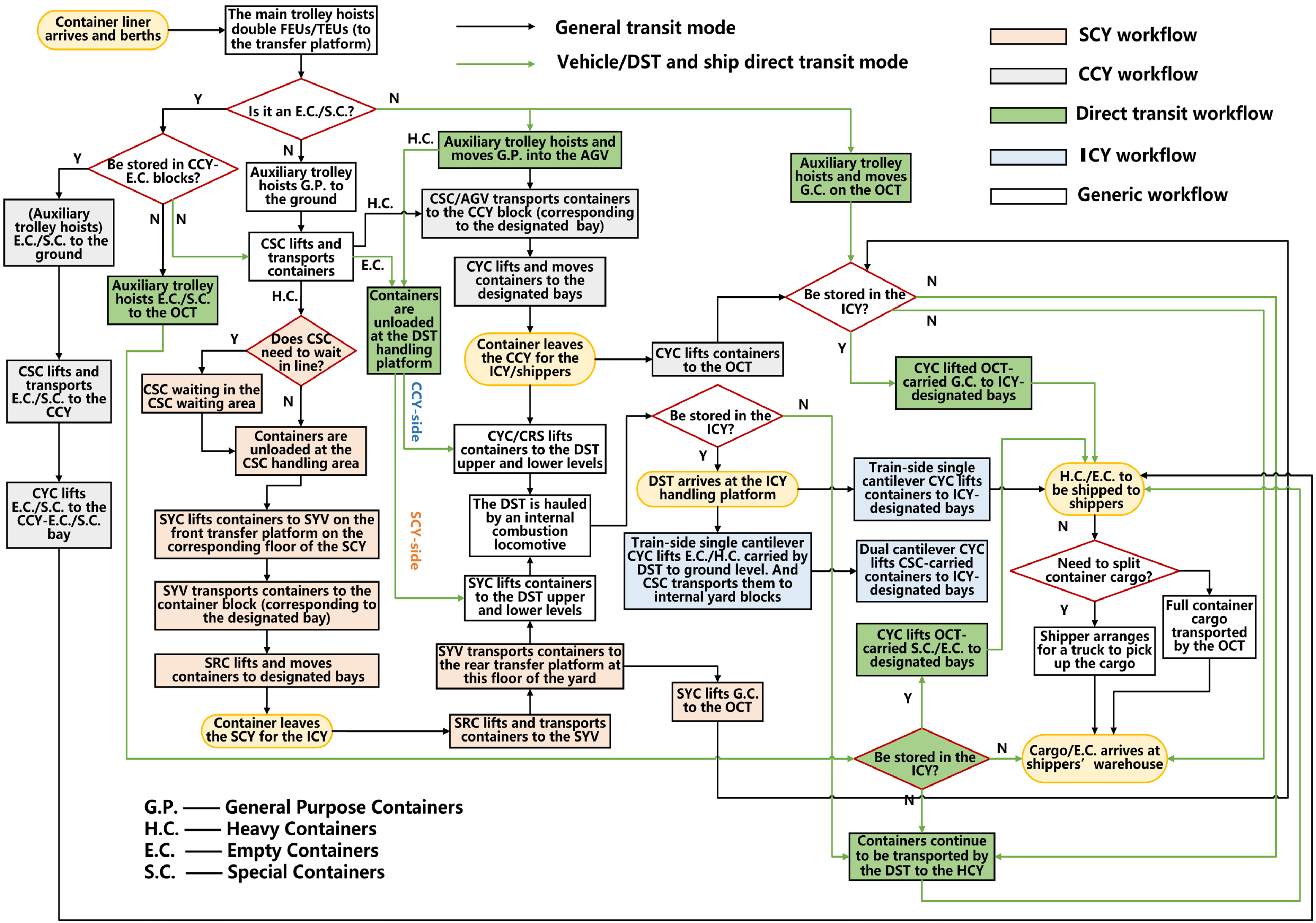
(1) Initialise the particle swarm: a certain number of particles are randomly generated, and each particle represents a candidate solution.
(2) Evaluate particle fitness: evaluate the objective function for each particle to get its fitness in the objective space.
(3) Update Pbest: Update the individual best position (Personable best, Pbest) of each particle according to its fitness.
(4) Update Gbest: Select the global best solution (Global best, Gbest), which is the optimal solution on the Pareto front, from all Pbests.
(5) Update Particle Velocity and Position: update the particle velocity and position based on the current position and velocity of the particle, as well as the individual and global optimal positions.
(6) Repeat iteration: check the stopping condition, if the stopping condition is not fulfilled (the maximum number of iterations is reached or the convergence condition is reached), then repeat the execution of step 2 to step 5.



Main text Figure 10. INSGA-II and MOPSO workflow

3. Operational procedure

To illustrate the Main text Figure 8, each operation segment is numbered, and the specific flow of different operation scenarios in the indirect transshipment mode and the direct transshipment mode is summarized in Annex Table 1; the English abbreviations and their implications in each process are detailed in the Main text Table 2.



Main text Figure 8. Operational flow of the CCLS

Main Table 2. Expressions and abbreviations for key terms

Description	Abbreviation
Water port	WP
Dry port	DP
Collaborative Container Logistics System between a Dry Port and a Water Port	CCLS
Water-rail Transport of Double-stack Container Trains	WTDST
Stereo automated container yard	SCY
Conventional automated container yard	CCY
Inland automated container yard	ICY
Hinterland container freight station	HCFS
Stereoscopic yard rail crane	SYC
Conventional yard rail crane	CYC
Double trolley shore crane	DSC
Single trolley shore crane	SSC
Container straddle carrier	CSC
Container reach stacker	CRS
Suspended rail crane	SRC
Stereo yard vehicle	SYV
Automatic guided vehicle	AGV
Outside port container truck	OCT
Double-stack container train	DST
Forty-foot Equivalent Unit	FEU
Twenty-foot Equivalent Unit	TEU
Special-foot Equivalent Unit	SEU
Fodable Vehicle Rack	FVR

Annex Table 1. Import container operation process

<table>
<tr><th rowspan="4">Segment</th><th colspan="6">Indirect transshipment mode</th><th colspan="4">Direct transshipment mode</th></tr>
<tr><th colspan="2" rowspan="2">SCY operation</th><th colspan="4">CCY operation</th><th colspan="2" rowspan="2">Train-vessel transshipment</th><th colspan="2" rowspan="2">Truck-vessel transshipment</th></tr>
<tr><th colspan="2">CSC operation</th><th colspan="2">AGV operation</th></tr>
<tr><th>DST</th><th>OCT</th><th>DST</th><th>OCT</th><th>DST</th><th>OCT</th><th>CSC</th><th>AGV</th><th>General containers</th><th>Special/empty containers</th></tr>
<tr><td>1</td><td colspan="6">(1)</td><td colspan="4">(1)</td></tr>
<tr><td>2</td><td colspan="4">(2)</td><td colspan="2">(3)</td><td>(2)</td><td>(3)</td><td colspan="2">(4)</td></tr>
<tr><td>3</td><td colspan="2">(5)</td><td colspan="2">(6)</td><td colspan="2">(7)</td><td>(8)</td><td>(9)</td><td colspan="2">(10)</td></tr>
<tr><td>4</td><td colspan="2">(11)</td><td colspan="4">(12)</td><td colspan="2">(13)</td><td colspan="2">(14)</td></tr>
<tr><td>5</td><td colspan="2">(15)</td><td>(16)</td><td>(17)</td><td>(16)</td><td>(17)</td><td colspan="2">(18)</td><td>-</td><td>-</td></tr>
<tr><td>6</td><td colspan="2">(19)</td><td>(18)</td><td>(10)</td><td>(18)</td><td>(10)</td><td colspan="2">(20)</td><td>-</td><td>-</td></tr>
<tr><td>7</td><td colspan="2">(21)</td><td>(20)</td><td>(14)</td><td>(20)</td><td>(14)</td><td colspan="2">(14)</td><td>-</td><td>-</td></tr>
<tr><td>8</td><td colspan="2">(22)</td><td>(14)</td><td>-</td><td>(14)</td><td>-</td><td>-</td><td>-</td><td>-</td><td></td></tr>
<tr><td>9</td><td>(23)</td><td>(24)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>10</td><td>(18)</td><td>(20)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>11</td><td>(20)</td><td>(14)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>12</td><td>(14)</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

The numbering of each operation of the imported general containers is as follows.
(1) DSC main trolley lifts the container to the transit platform.
(2) DSC auxiliary trolley lifts the container to the ground // SSC lifts the container to the ground (no need to number step 1 at this time).
(3) DSC lifts container to AGV // SSC lifts container to AGV (no need to number step 1 at this time).
(4) DSC lifts container to OCT // SSC lifts container to OCT (no need to number step 1 at this time).
(5) CSC lifts container to CSC handling area for unloading.
(6) CSC lifts the container to the CCY block corresponding to the designated bay.
(7) AGV transports the container to the CCY block corresponding to the designated bay.
(8) CSC lifts the container to the DST handling platform for unloading.
(9) The AGV transports the container to the DST handling platform and waits.
(10) When the container needs to be temporarily stored in ICY, CYC lifts the container carried by OCT to the designated ICY bay; otherwise, OCT transports the container to the shipper or HCS.
(11) SYC lifts the container to the SYV on the front transit platform on the corresponding floor of SCY.
(12) CYC lifts the container to the designated bay.
(13) CYC/CRS lifts containers on CCY side//SYC lifts containers on SCY side to DST.
(14) OCT delivers the full container directly to the shipper if the container does not need to be unpacked; otherwise, after

unpacking, the shipper arranges trucks to bring back the goods/empty container.
(15) SYV transports the container to the yard block corresponding to the designated bay.
(16) CYC/ CRS lifts the container for loading to DST.
(17) CYC lifts the container to OCT.
(18) DST is hauled by an internal combustion locomotive and then replaced by an electric locomotive for transport.
(19) SRC lifts the container to the designated bay.
(20) When containers need to be temporarily stored in ICY, CYC lifts containers carried by DST to designated bays, divided into two cases: **(a)** After DST arrives at the ICY handling platform, the train-side single cantilever CYC lifts containers carried by DST to designated bays at ICY; **(b)** After DST arrives at the ICY handling platform, the train-side single cantilever CYC lifts containers carried by DST to the ground and transports them to the internal yard bays by CSC, and finally the double-cantilever CYC lifts the containers to the designated box space at ICY. If containers do not need to be temporarily stored in ICY, DST will transport the containers to HCS.
(21) SRC lifts the container to the SYV in the yard on this floor.
(22) SYV transports the containers to the rear transit platform of this yard floor.
(23) SYC lifts the container to DST.
(24) SYC lifts the container to OCT.

4. The initial occupied and remaining number of bays in each yard block

Annex Table 2. Initial number of occupied bays and remaining bays for each SCY heavy container block

sh	b_{sh}	k_{sh}	sh	b_{sh}	k_{sh}	sh	b_{sh}	k_{sh}	sh	b_{sh}	k_{sh}	sh	b_{sh}	k_{sh}	sh	b_{sh}	k_{sh}
1	111	89	6	72	128	11	75	125	16	65	135	21	120	80	26	136	64
2	85	115	7	73	127	12	59	141	17	111	89	22	83	117	27	73	127
3	130	70	8	121	79	13	129	71	18	74	126	23	125	75	28	89	111
4	62	138	9	125	75	14	103	97	19	146	54	24	98	102	29	76	124
5	126	74	10	109	91	15	64	136	20	119	81	25	139	61	30	142	58

Annex Table 3. Initial number of occupied bays and remaining bays for each ICY heavy container block

ih	b_{ih}	k_{ih}	ih	b_{ih}	k_{ih}	ih	b_{ih}	k_{ih}	ih	b_{ih}	k_{ih}	ih	b_{ih}	k_{ih}
1	136	104	6	115	125	11	61	179	16	71	169	21	70	170
2	84	156	7	173	67	12	110	130	17	82	158	22	133	107
3	158	82	8	71	169	13	161	79	18	120	120	23	93	147
4	116	124	9	172	68	14	102	138	19	103	137	24	94	146
5	139	101	10	81	159	15	163	77	20	119	121	25	171	69

Annex Table 4. Initial number of occupied bays and remaining bays for each CCY empty container block

ce	b_{ce}	k_{ce}	ce	b_{ce}	k_{ce}
1	158	242	6	203	197
2	166	234	7	235	165
3	181	219	8	130	270
4	231	169	9	242	158
5	103	297	10	101	299

Annex Table 5. Initial number of occupied bays and remaining bays for each ICY empty container block

ie	b_{ie}	k_{ie}	ie	b_{ie}	k_{ie}	ie	b_{ie}	k_{ie}	ie	b_{ie}	k_{ie}
1	91	229	6	137	183	11	194	126	16	202	118
2	196	124	7	204	116	12	233	87	17	170	150
3	192	128	8	154	166	13	177	143	18	84	236
4	207	113	9	165	155	14	230	90	19	181	139
5	90	230	10	238	82	15	100	220	20	87	233