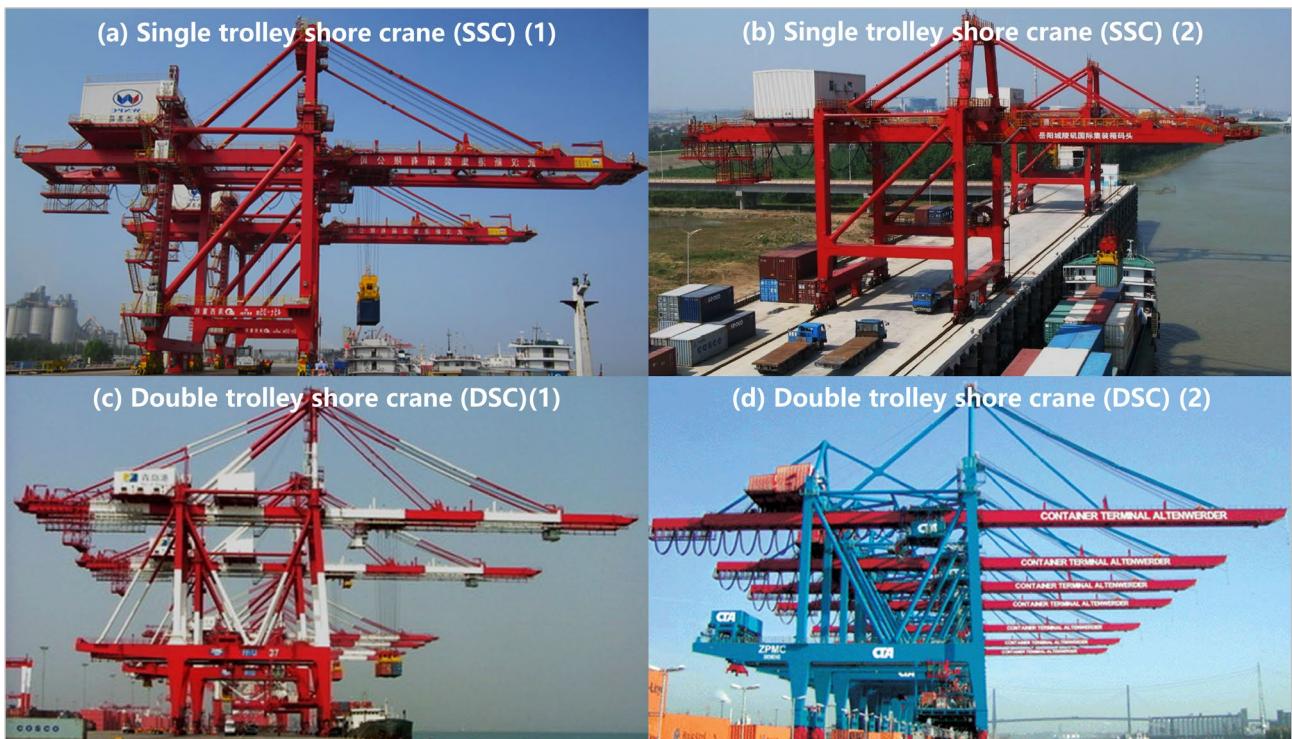


Supplementary materials for *Design and optimization of the dual-terminal collection and distribution system*

1. Elemental components of the DTDCS

1.1 Shore handling equipment

The CCY employs the traditional single trolley shore crane (SSC) for container handling on the sea side, as depicted 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

Figure 4 illustrates various types of conventional yard rail cranes (CYC). The CCY utilizes double cantilever CYC on both the sea and the land sides, while 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.



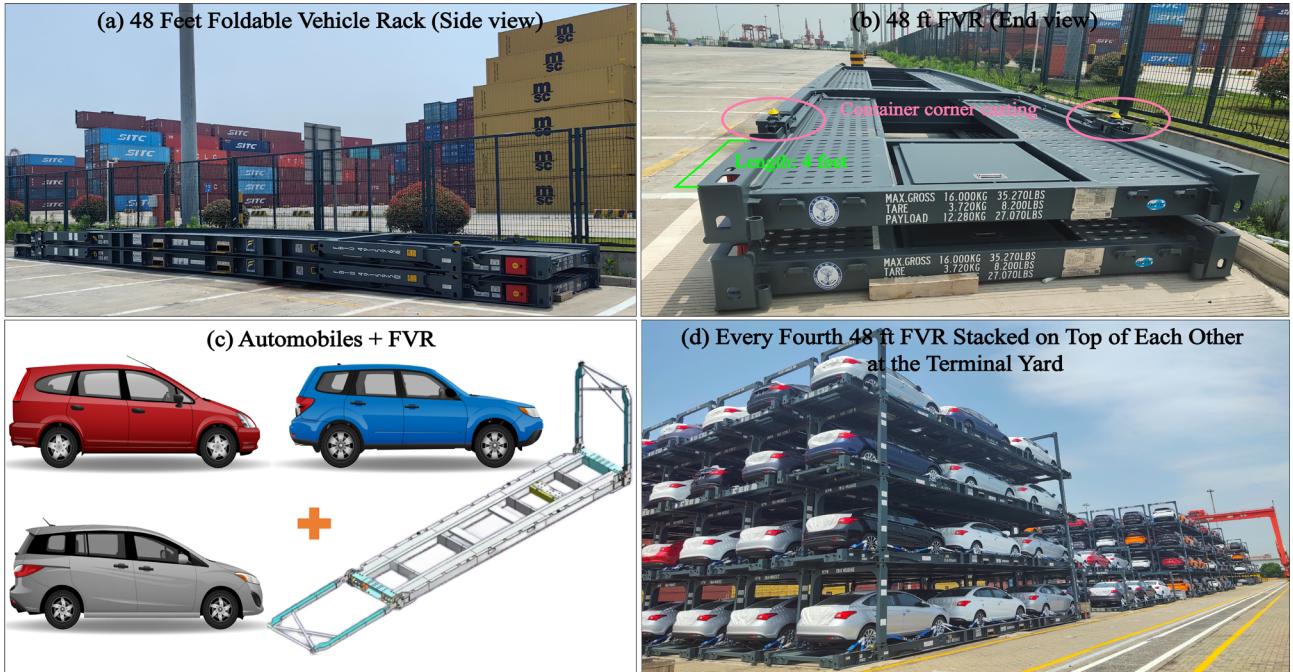
Annex Figure 2. Yard handling equipments

1.3 Horizontal transport equipment

In the WCT 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.

2.2 MOPSO

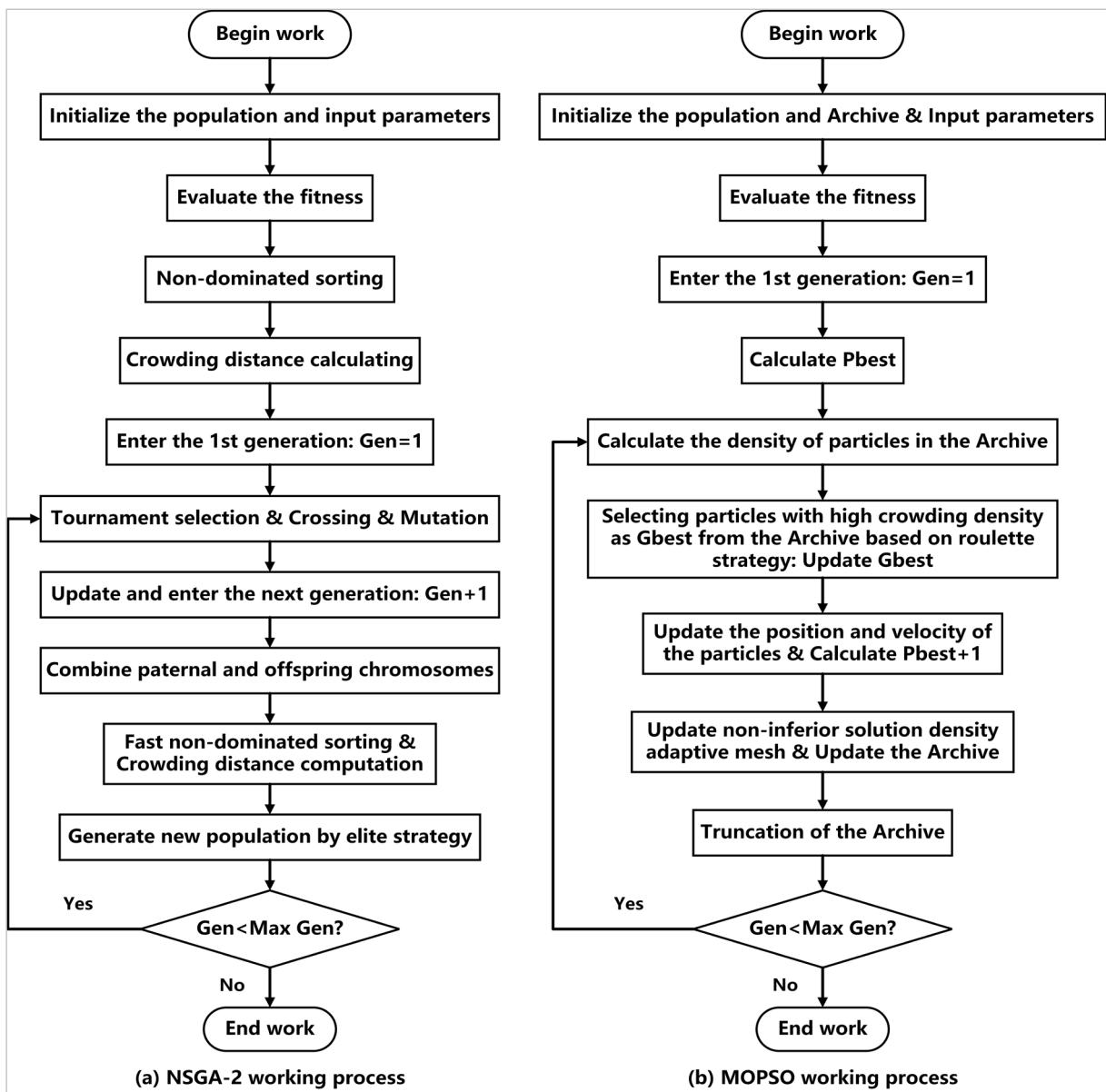
The Multi-objective Particle Swarm Optimization (MOPSO) algorithm was proposed by (Coello et al., 2004; Coello and Lechuga, 2002). It searches and obtains the set of Pareto frontier solutions in solving multi-objective optimization problems to provide a balanced set of solutions. The advantages of MOPSO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

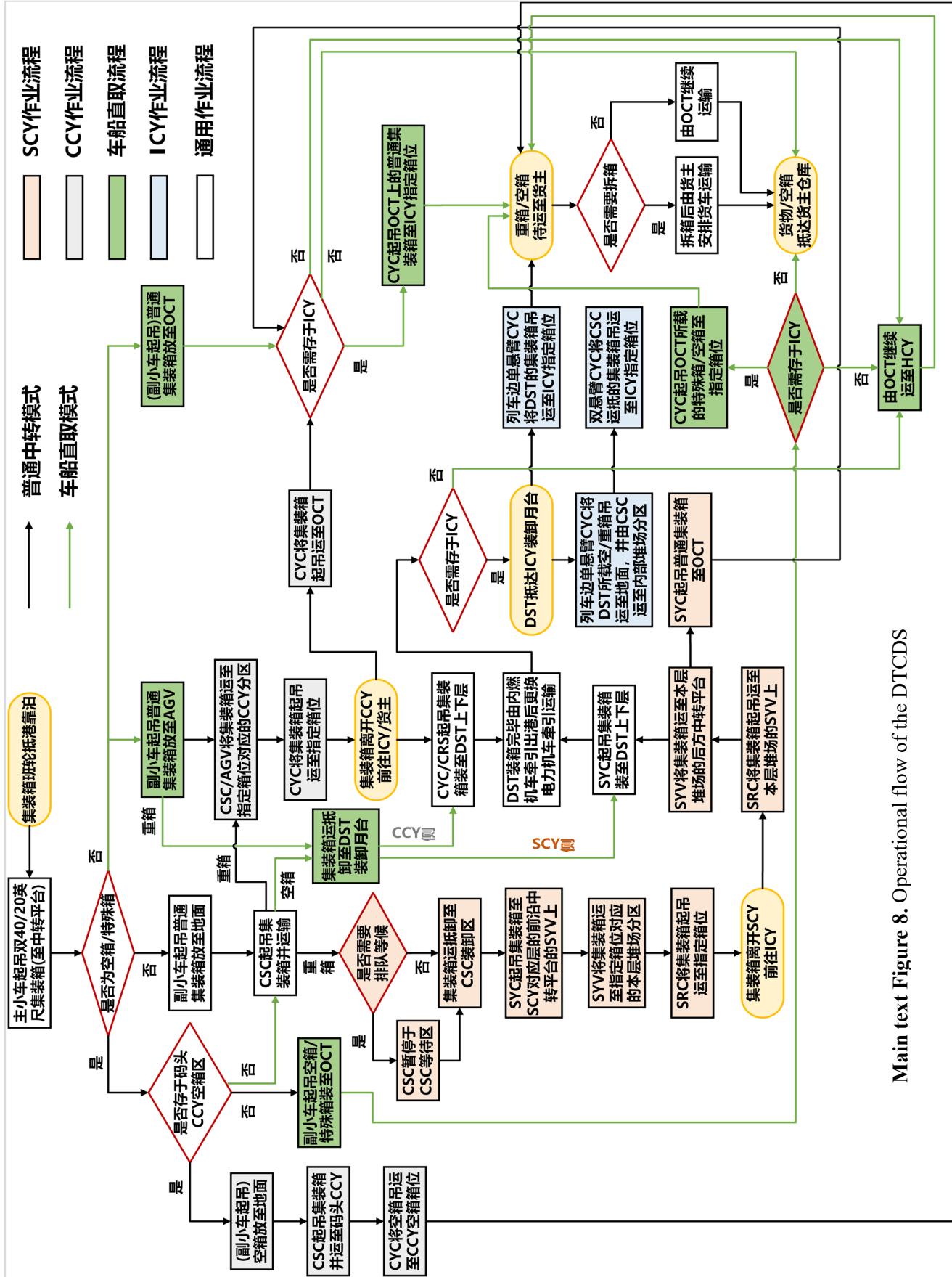
- (1) Initialise the particle swarm: a certain number of particles are randomly generated, and each particle represents a candidate solution.
- (2) Evaluate particle fitness: evaluate the objective function for each particle to get its fitness in the objective space.
- (3) Update Pbest: Update the individual 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. NSGA-II and MOPSO work flow

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 1.



Main text Figure 8. Operational flow of the DTCDs

Main Table 1. Expressions and abbreviations for key terms

Description	Abbreviation
Stereo automated container yard	SCY
Inland automated container yard	ICY
Hinterland road-rail intermodal container yard	HCY
Conventional automated container yard	CCY
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

Annex Table 1. Import container operation process

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

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

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

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

<i>ih</i>	<i>b_{ih}</i>	<i>k_{ih}</i>												
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 3. Initial number of occupied bays and remaining bays for each CCY empty container block

<i>ce</i>	<i>b_{ce}</i>	<i>k_{ce}</i>	<i>ce</i>	<i>b_{ce}</i>	<i>k_{ce}</i>
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 4. Initial number of occupied bays and remaining bays for each ICY empty container block

<i>ie</i>	<i>b_{ie}</i>	<i>k_{ie}</i>									
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