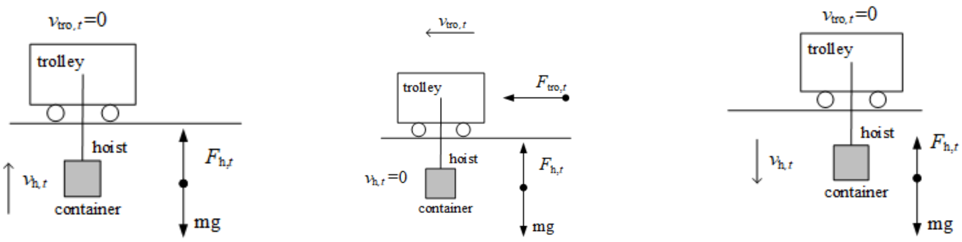
Appendix A1: Linearized equation of Constraint(10)

$$\begin{cases} D_{m,s} \le \sum_{p=1}^{t} N_{m,t,s}^{\text{con}} + M \cdot (1 - W_{m,t,s}) \\ D_{m,s} \ge \sum_{p=1}^{t} N_{m,t,s}^{\text{con}} - M \cdot W_{m,t,s} \\ \sum_{p=1}^{t} N_{m,t,s}^{\text{con}} \le D_{m,s} + M \cdot W_{m,t,s} \\ \sum_{p=1}^{t} N_{m,t,s}^{\text{con}} \ge D_{m,s} - M \cdot (1 - W_{m,t,s}) \end{cases}, \forall m,t,s \tag{1}$$

Appendix A2: Dynamic modeling of single AQC

The container handling operations of an Automated Quay Crane (AQC) can be categorized into two types: container loading and container unloading. Taking the loading operation as an example, under the single-cycle mode, where loading tasks are initiated only after the completion of all unloading tasks, the loading process of a container by an AQC proceeds as follows: the spreader first vertically lifts the container (i.e., loaded state); the trolley then carries the container horizontally from the quay side to the vessel side and positions it at the designated location; subsequently, the spreader lowers the container and releases it into the ship hold, transitioning to an unloaded state; finally, the spreader returns to the quay side through a sequence of hoisting, horizontal movement, and lowering. Therefore, each container loading task involves 6 sequential operations: loaded hoisting, loaded trolley-traversing, loaded descending, unloaded hoisting, unloaded trolley-traversing and unloaded descending, denoted by action index *j*, and $j \in \{1,2,3,4,5,6\}$.

A force analysis is conducted for each of the above operations. Neglecting frictional losses, the corresponding dynamic models for the 6 operations, namely loaded hoisting, loaded trolley-traversing, loaded descending, unloaded hoisting, unloaded trolley-traversing, and unloaded descending, are formulated as (2)-(7). In these formulations: $F_{n,i,t}^{\text{h}}$ denotes the net vertical force acting on the spreader of AQC n handling container i at time t. $a_{n,i,t}^{\text{h}}$ denotes the vertical acceleration of the spreader when lifting or lowering container i. $F_{n,i,t}^{\text{tro}}$ denotes the net horizontal force acting on the trolley. $a_{n,i,t}^{\text{tro}}$ denotes the horizontal acceleration of the trolley. m_{hoist}、m_{trolley}、m_{con} represent the masses of the spreader, trolley, and container, respectively. g is the gravitational acceleration. N^{qc} denotes the set of all scheduled quay cranes. N_n^{con} denotes the set of container handling tasks assigned to AQC n. Fig.1(a), (b), and (c) illustrate the force analysis diagrams for loaded hoisting, loaded trolley-traversing, and loaded descending operations, respectively. The force analysis for the remaining operations follows a similar methodology。



(a)loaded hoisting (b) loaded trolley-traversing (c) loaded descending

Fig. 1 Force analysis for AQC of different actions

$$\begin{cases} F_{n,i,t}^{\mathrm{h}} = (m_{\mathrm{hoist}} + m_{\mathrm{con}})g + (m_{\mathrm{hoist}} + m_{\mathrm{con}})a_{n,i,t}^{\mathrm{h}} \\ F_{n,i,t}^{\mathrm{tro}} = 0 \end{cases}, \quad (2)$$
$$\forall n \in N^{\mathrm{qc}}, i \in N_n^{\mathrm{con}}, t \in T, j = 1$$

$$\begin{cases} F_{n,i,t}^{\mathrm{h}} = (m_{\mathrm{hoist}} + m_{con})g \\ F_{n,i,t}^{\mathrm{tro}} = (m_{\mathrm{trolley}} + m_{\mathrm{hoist}} + m_{con})a_{n,i,t}^{\mathrm{tro}} \end{cases}, \quad (3)$$
$$\forall n \in N^{\mathrm{qc}}, i \in N_n^{\mathrm{con}}, t \in T, j = 2$$

$$\begin{cases} F_{n,i,t}^{\mathrm{h}} = (m_{\mathrm{hoist}} + m_{\mathrm{con}})g - (m_{\mathrm{hoist}} + m_{\mathrm{con}})a_{n,i,t}^{\mathrm{h}} \\ F_{n,i,t}^{\mathrm{tro}} = 0 \end{cases}, \quad (4)$$
$$\forall n \in N^{\mathrm{qc}}, i \in N_n^{\mathrm{con}}, t \in T, j = 3$$

$$\begin{cases} F_{n,i,t}^{\mathrm{h}} = m_{\mathrm{hoist}}g + m_{\mathrm{hoist}}a_{n,i,t}^{\mathrm{h}} \\ F_{n,i,t}^{\mathrm{tro}} = 0 \end{cases}, \quad (5)$$
$$\forall n \in N^{\mathrm{qc}}, i \in N_n^{\mathrm{con}}, t \in T, j = 4$$

$$\begin{cases} F_{n,i,t}^{\mathrm{h}} = m_{\mathrm{hoist}}g \\ F_{n,i,t}^{\mathrm{tro}} = (m_{\mathrm{trolley}} + m_{\mathrm{hoist}})a_{n,i,t}^{\mathrm{tro}} \end{cases}, \quad (6)$$
$$\forall n \in N^{\mathrm{qc}}, i \in N_n^{\mathrm{con}}, t \in T, j = 5$$

$$\begin{cases} F_{n,i,t}^{\mathrm{h}} = m_{\mathrm{hoist}}g - m_{\mathrm{hoist}}a_{n,i,t}^{\mathrm{h}} \\ F_{n,i,t}^{\mathrm{tro}} = 0 \end{cases}, \quad (7)$$
$$\forall n \in N^{\mathrm{qc}}, i \in N_n^{\mathrm{con}}, t \in T, j = 6$$

Each individual operation of the Automated Quay Crane (AQC) is divided into three phases: acceleration, constant velocity, and deceleration. It is assumed that the acceleration within each operation is constant. Specifically, the AQC first undergoes uniform acceleration for a duration $T_{n,i,j}^{\mathrm{a}}$, reaching a maximum velocity $v_{n,i,j}^{\mathrm{s}}$. This is followed by a constant-velocity phase at $v_{n,i,j}^{\mathrm{s}}$, lasting $T_{n,i,j}^{\mathrm{s}}$. And finally, a uniform deceleration phase of duration $T_{n,i,j}^{\mathrm{d}}$ bringing the velocity to zero. Let $T_{n,i,j}$ denote the total duration required by AQC *n* to complete action *j* for container *i*, and $t_{n,i,j}^{\mathrm{st}}$, $t_{n,i,j}^{\mathrm{ed}}$ represent the start and end times of this action, respectively. The acceleration associated with each crane operation is defined in (8)。

$$a_{n,i,t}^{\mathrm{h/tro}} = \begin{cases} T_{n,i,j}^{\mathrm{a}} / v_{n,i,j}^{\mathrm{s}}, t \in [t_{n,i,j}^{\mathrm{st}}, t_{n,i,j}^{\mathrm{st}} + T_{n,i,j}^{\mathrm{a}}] \\ 0, \qquad t \in [t_{n,i,j}^{\mathrm{st}} + T_{n,i,j}^{\mathrm{a}}, t_{n,i,j}^{\mathrm{st}} + T_{n,i,j}^{\mathrm{a}} + T_{n,i,j}^{\mathrm{s}}], \\ T_{n,i,j}^{\mathrm{d}} / v_{n,i,j}^{\mathrm{s}}, t \in [t_{n,i,j}^{\mathrm{st}} + T_{n,i,j}^{\mathrm{a}} + T_{n,i,j}^{\mathrm{s}}, t_{n,i,j}^{\mathrm{ed}}] \end{cases} \quad (8)$$
$$\forall n, i, j, t$$

Appendix A3: Vessel logistics information in Case study

Tab.1 Ship-side power demand and total container tasks of each vessel

Vessel Number	Power demand on OPS /MW	Total container tasks /TEU	Estimated arrival time
1	0.3	400	1
2	0.4	500	4
3	0.2	300	3
4	0.4	500	4
5	0.2	200	1
6	0.3	450	8
7	0.4	600	9
8	0.2	200	10
9	0.4	450	16
10	0.3	200	17
11	0.2	150	18
12	0.3	200	18

Scenario 1 represents the baseline case in which all vessels arrive at the port on schedule. Given that port operations are typically organized into three 8-hour shifts, the remaining scenarios capture potential deviations from the baseline due to vessel delays or cancellations. Specifically, in Scenario 2, Vessel 2 experiences a delay and is rescheduled to berth at time t=8. In Scenario 3, Vessel 5 is delayed and reassigned to berth at t=16. Scenario 4 assumes a delay of Vessel 8, which is also rescheduled to berth at t=16. Scenario 5 reflects a cancellation, where Vessel 12 does not arrive at the port. The associated probabilities for Scenarios 1 through 5 are 0.5, 0.1, 0.2, 0.15, and 0.05, respectively.

Appendix A4: AQC operation & energy-related parameters in Case study

Based on the actual operating conditions of a representative U.S. port, the key spatial parameters illustrated in Fig.4 of the manuscript are as follows: the vertical distance from the vessel deck bottom to the AQC gantry beam H_1 is 40 m; the height from the quay-side transfer vehicle chassis to the gantry beam H_2 is 35 m; and the horizontal distance from the vessel's starboard side to the quay-side container stacking point L is 30 m. Each container has a length of 5 m and a height of 2.5 m. In the day-ahead scheduling stage, the energy consumption of the AQC is assumed to be 4 kW per TEU.

Lithium titanate batteries are selected as the energy storage system, with the number of allowable equivalent full cycles set to 750.

The operational speed limits and time constraints for each AQC movement are provided in Table 2. Mechanical parameters of the AQC and relevant energy supply characteristics are detailed in Tables 3 and 4, respectively. Table 5 specifies the container handling sequence, where a lower container index indicates earlier processing. The coordinate values indicate the target stowage location of each container within the ship hold.

All computational experiments are conducted on a hardware platform equipped with an Intel(R) Core(TM) i7-8750H CPU @ 2.20 GHz and 8 GB of RAM. The model is implemented in Python using PyCharm 2023.1 and solved with the commercial optimization solver Gurobi 10.9.

Tab.2 Main parameters of quay crane operation

Action	Min/Max Acceleration Time (s)	Min/Max Constant-Velocity Time (s)	Min/Max Deceleration Time (s)	Max Constant Velocity (m/s)
Loaded Hoisting	3/20	0/100	3/20	1.5
Loaded Trolley-traversing	3/20	0/100	3/20	2.0
Loaded Descending	5/30	0/100	5/30	1.5
Unloaded Hoisting	2/15	0/100	2/15	2.0
Unloaded Trolley-traversing	2/15	0/100	2/15	3
Unloaded Descending	2/15	0/100	2/15	2

Tab.3 Quay crane mechanical parameters

Parameter	Symbol	Value	Parameter	Symbol	Value
Gear Transmission Efficiency	η_1	0.85	Spreader Mass	m_{hoist}	12000kg
Hoist/Trolley Motor Regenerative Efficiency	$\eta_{\mathrm{s}} / \eta_{\mathrm{t}}$	0.7	Trolley Mass	m_{trolley}	8000kg
Gravitational Acceleration	g	9.8m/s^2	Container Mass	m_{con}	80000kg

Tab.4 Energy-related parameters

Parameter	Symbol	Value	Parameter	Symbol	Value
Charging/Discharging Efficiency of Energy Storage System	$\eta_{\mathrm{dch}} / \eta_{\mathrm{ch}}$	0.9/0.9	Maximum Grid Purchase Power	$P_{\mathrm{grid}}^{\mathrm{max}}$	3000kW
Maximum Charging/Discharging Power per Cycle of Energy Storage System	$P_{\mathrm{dch}}^{\mathrm{max}} / P_{\mathrm{ch}}^{\mathrm{max}}$	600/600kW	Penalty Coefficient for Wind and Solar Curtailment	α_{cur}	0.1$/kWh
Energy Storage Capacity	C	6000kWh	\	\	\

Tab.5 Container loading sequence

Index	Coordinate	Index	Coordinate	Index	Coordinate	Index	Coordinate	Index	Coordinate
1	(1,5,5)	2	(1,4,5)	3	(1,3,5)	4	(1,2,5)	5	(1,1,5)
6	(1,5,4)	7	(1,4,4)	8	(1,3,4)	9	(1,2,4)	10	(1,1,4)
…	…	…	…	…	…	…	…	…	…
21	(1,5,1)	22	(1,4,1)	23	(1,3,1)	24	(1,2,1)	25	(1,1,1)
26	(2,5,5)	27	(2,4,4)	28	(2,3,4)	29	(2,2,4)	30	(2,1,4)
…	…	…	…	…	…	…	…	…	…