Postprint: Multi-AGV Scheduling Optimization in Automated Container Terminals Considering Battery Pack Quantity

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Abstract

A bi-level programming model is established to address the actual battery swapping characteristics of automated guided vehicles (AGVs) in automated container terminals, aiming to reduce the total task completion time and total battery swapping time of AGVs while rationally planning the number of battery packs in battery swapping stations. First, considering the battery endurance of AGVs, the SOC variation characteristics under empty and loaded conditions, and the relationship between different remaining power levels and speed changes, an upper-level model for multi-AGV container task scheduling considering battery swapping is constructed with the objective of minimizing the total task completion time of AGVs. On this basis, to rationally plan the number of battery packs in battery swapping stations and considering the actual battery pack selection principles and swapping processes in automated terminals, a lower-level model for battery pack configuration in swapping stations is constructed with the objective of minimizing the total battery swapping time, which makes decisions on the selection of swapping stations and battery packs. Finally, genetic algorithms are employed to solve small-scale and large-scale case examples respectively. The computational results demonstrate that this bi-level programming model can effectively reduce total task completion time and total battery swapping time, increase AGV utilization by 6.46%, and reduce the number of battery packs in swapping stations by 23.1%.

Full Text

Preamble

Research on Multi-AGV Scheduling Optimization in Automated Container Terminals Considering Battery Pack Quantity

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Abstract: In view of the actual battery swapping characteristics of Automated Guided Vehicles (AGVs) in automated container terminals, this paper establishes a bi-level programming model to reduce the total task completion time and total battery swapping time while rationally planning the number of battery packs in swapping stations. First, considering AGV battery endurance, State of Charge (SOC) variation characteristics under loaded and unloaded conditions, and speed variations at different residual power levels, an upper-level model for multi-AGV container task scheduling with battery swapping considerations is constructed to minimize total task completion time. On this basis, to rationally plan the number of battery packs in swapping stations, a lower-level model for battery pack configuration is developed with the objective of minimizing total swapping time, considering the actual battery pack selection principles and swapping processes in automated terminal swapping stations to make decisions on station and battery pack selection. Finally, genetic algorithms are used to solve both small-scale and large-scale examples. The results demonstrate that this bi-level programming model can effectively reduce total task completion time and total swapping time, improve AGV utilization by 6.46%, and reduce the number of battery packs in swapping stations by 23.1%.

Keywords: automated container terminal; automated guided vehicle; genetic algorithm; number of battery packs

0 Introduction

Container terminals play a crucial role in connecting sea-land logistics transportation. With the comprehensive development of global economic integration and the deepening implementation of the "global village" concept, the advantages of traditional container terminals—such as high transportation efficiency and good safety—can no longer meet the needs of global economic development. Compared to traditional terminals, automated container terminals are characterized by automated and intelligent operations for container loading/unloading, yard operations, and horizontal transportation. In the operational areas of the entire terminal and yard, human participation is eliminated, and electrically-driven AGVs perform container loading, unloading, and transportation tasks. Consequently, the operational efficiency of purely electric-powered AGVs largely determines the overall efficiency of the container terminal.

The power status of AGVs can be described by State of Charge (SOC), which represents the ratio of remaining dischargeable capacity to fully charged capacity after a period of use or long-term storage, typically expressed as a percentage. Kim et al. [1] adopted a time-event approach for AGV scheduling problems, allocating tasks to AGVs with objectives of minimizing AGV working time and vessel delay time. Frank Schneider et al. [2] established a battery swapping station network and proposed a dynamic programming model to assist optimal charging decisions, with results effectively determining whether to charge batteries based on dynamic electricity prices. Xi Xiang et al. [3] proposed a nested semi-open queuing network model for performance evaluation of automated container terminals considering battery management, optimizing system resource allocation and layout design based on approximate solutions. Shi Nanlu et al. [4] constructed a mixed-integer scheduling model considering the AGV swapping process to reduce the impact of battery swapping on scheduling and improve AGV work efficiency. Zhou Xiaofan et al. [5] established an AGV scheduling model minimizing task completion time, considering AGV battery endurance and power consumption differences between loaded and unloaded conditions. Zhang Yaqi et al. [6] developed an AGV operation scheduling model maximizing charging utilization, minimizing final task completion time, and minimizing AGV empty travel time, based on charging requirements and transportation characteristics of electric AGVs, considering vertical yard layout and charging process impacts. Wu Hongming et al. [7] established an AGV scheduling model minimizing total task completion time, considering empty/heavy load power consumption characteristics and nonlinear charging features to improve automated container terminal AGV operational efficiency. Ding Yi et al. [8] addressed dynamic scheduling of multi-load AGVs, considering load capacity and post-charging endurance, using a hybrid cycle-event driven rolling horizon optimization strategy to construct a mixed-integer programming model for dynamic AGV operation scheduling. Zheng Yahong et al. [9] built a collaborative scheduling optimization model for AGV operations and battery swapping to reduce queue waiting time at swapping stations, designing a genetic algorithm to solve the model. Fu Zhengtang et al. [10] studied AGV power discharge characteristics in non-saturated states, establishing and solving a mathematical model using CPLEX. Fan Houming et al. [11] employed a two-stage modeling approach, designing enumeration and genetic algorithms for joint configuration of dual-trolley quay cranes and AGVs. Song Shaojing et al. [12] established a mathematical model maximizing AGV work efficiency to rationally plan AGV quantity, verifying effectiveness through practical application scenarios. Huang Yuchao [13] analyzed swapping station layout design, equipment layout, and AGV scheduling systems, designing new layout solutions validated through comparative analysis. Fan Lubin et al. [14] established truck dispatching and configuration sub-models from an uncertainty perspective, connecting them through completion time and truck quantity as shared design variables, solving the coupled model to effectively reduce delay costs and truck quantity. Chen Xiangling et al. [15] proposed mixed-integer programming (MIP) and constraint programming (CP) models minimizing sorting operation cycles, considering AGV power consumption during handling and charging characteristics, AGV residual power, and package time windows, verifying model effectiveness through case analysis.

In summary, existing research on AGV scheduling in automated container terminals primarily focuses on battery swapping modes and strategies, without comprehensive consideration of factors affecting AGV battery swapping. Building upon previous studies, this paper first considers AGV battery endurance, loaded/unloaded SOC variation characteristics, and speed variations at different residual power levels to improve battery pack utilization. An upper-level model for AGV container task scheduling with battery swapping considerations is constructed to minimize total task completion time. To schedule swapping tasks generated during container task scheduling and rationally plan battery pack quantity in swapping stations, this paper considers actual battery pack selection principles and swapping processes in automated terminals, making decisions on station and battery pack selection. A lower-level battery pack configuration model is developed to minimize total swapping time, forming a bi-level model that addresses both container task scheduling and battery swapping task scheduling.

1 Problem Description

Figure 1 illustrates the actual layout of a vertical automated container terminal, which can be divided into three zones: automated yard, AGV operating area, and quay crane operating area. Swapping stations and supporting facilities require substantial space and are typically located on both sides at the ends of AGV main travel routes. In automated container terminals, pure electric AGVs perform container loading, unloading, and transportation tasks, moving containers to corresponding yard buffer zones and quay crane buffer zones.

In mixed loading/unloading operations, an AGV' s current export container task might start at Yard 3. The AGV travels to the interaction area at Yard 3, picks up the export container from the buffer 支架, transports it via main travel routes to the corresponding quay crane portal trolley for container handover. If the next import container' s origin is not at this quay crane' s transfer platform, the AGV travels empty to the quay crane where the import container is located, picks it up, and transports it to the destination Yard 1.

After completing a container task, the AGV' s residual power must be evaluated against thresholds to determine if it can complete the next task. If not, the AGV must perform a battery swapping task; otherwise, it continues with container tasks. Additionally, the AGV selects different operating speeds based on its residual power—when residual power is low, speed is reduced to improve battery utilization.

In actual swapping stations, hardware primarily consists of swapping robots, charging units, and battery warehouses. The battery pack replacement process is: when an AGV requiring battery swap approaches the target station, it enters from one end, arrives at the designated swapping position, and the swapping robot selects a suitable battery pack from the warehouse to replace the AGV' s battery. At Yangshan Port Phase IV automated terminal, the average battery pack replacement operation time is 300 seconds. Simultaneously, charging units charge the depleted battery pack removed from the AGV. After replacement, the AGV exits from the other end of the station and proceeds to the next task' s origin position to continue operations.

As shown in Figure 2, when an AGV generates a battery swapping demand, it first evaluates total swapping time to different stations to decide between large or small stations, then executes the swapping task. When an AGV arrives at a station' s swapping position, the swapping robot must decide on battery pack selection, prioritizing fully charged packs or those with highest SOC in the warehouse. Since stations operate in a "swap-while-charging" mode—where the swapping robot selects packs while charging units charge insufficiently charged packs—there exists a minimum allowable swapping power level Pv. If all battery packs in the warehouse have SOC below Pv, the AGV must wait until a pack charges to Pv before swapping. When multiple packs with equally high SOC are available, the pack with more usage cycles is selected.

2.1.1 Model Assumptions

a) Initial AGV battery power is 100%; b) Equipment failures and collisions are not considered during operations; c) Operation sequences and times for each quay crane and yard crane task are known; d) All containers are 40 feet, and one AGV carries one container per trip.

2.1.2 Symbol Description

Symbols used in the upper-level model are described in Table 1.

Table 1 Symbol Description of Upper-Level Model

V0={v} - Virtual start task set
V' 0 - Virtual end task set
Vt={1,2,3,4,⋯..} - Loading/unloading task set
K={1,2,3,4,⋯..} - AGV set
Vbk - Battery swapping task set for AGV k
Vb=Vb1 Vb2 Vb3 ⋯- All battery swapping task sets
V=Vt Vb V' 0 V'' 00 - Complete task set
s1k, s2k - Empty/loaded speed of AGV k when executing task i
r - Power consumption percentage per second for AGV in empty/heavy load and parking
MC - Minimum power level for executing swapping tasks
fix - Average operation time of quay crane/yard crane
a - Time for one battery pack replacement operation
Wkij - Queuing time for AGV k executing swapping task i
Diq - Distance between task origin and destination
ei - Earliest allowed start time for task i
Dij - Distance between task i' s end point and task j' s start point
edki - Empty travel distance for executing task i, from predecessor task' s end to task i' s start
Cki - Completion time of task i by AGV k
Wiak - Waiting time at quay side for AGV k executing task i
bkii - Battery pack remaining power percentage when AGV k starts task i

bkij - Battery pack remaining power percentage when AGV k completes task i
xijk - Decision variable: equals 1 if AGV k executes task j after task i, otherwise 0

2.1.3 Model Formulation

Equation (1) is the objective function minimizing makespan. Equation (2) ensures final task completion time is no less than any task' s completion time. Equations (3) and (4) require each AGV to complete virtual start and end tasks. Equations (5) and (6) ensure each task has exactly one predecessor and one successor. Equation (7) balances intermediate tasks (input equals output). Equation (8) calculates empty travel distance during AGV task execution. Equation (9) calculates waiting time for regular and swapping tasks. Equation (10) calculates completion time for regular and swapping tasks. Equation (11) updates AGV residual power at task start. Equation (12) ensures AGV residual power is no greater than swapping threshold at swapping task start. Equation (13) updates AGV residual power upon task completion (100% after swapping). Equation (14) restricts AGVs to executing only their own n virtual swapping tasks. Equation (15) limits total swapping times per AGV to maximum s times. Equation (16) ensures an AGV completing i swaps can only finish the first i swapping tasks. Equations (17) and (18) define speed differences under various residual power levels. Equations (19) and (20) specify variable constraints.

2.2.1 Model Assumptions

a) Swapping position maintenance is not considered; b) Each swapping station follows first-come-first-served principle; c) Initial battery power in warehouse is 100%; d) Each swapping position serves only one AGV at a time; e) Battery pack lifespan and cost impacts are not considered.

2.2.2 Symbol Description

Symbols used in the lower-level model are described in Table 2.

2.2.3 Model Formulation

Equation (21) is the objective function minimizing total AGV swapping time. Equation (22) calculates total AGV swapping time. Equation (23) ensures an AGV selects only one swapping station per swap. Equation (24) ensures each battery pack serves only one AGV per swapping task. Equation (25) updates AGV battery power after swapping. Equation (26) calculates arrival time at swapping station (sum of swapping command generation time and empty travel time). Equation (27) updates AGV battery pack power after swapping (selected battery must exceed minimum allowable swapping power EC). Equation (28) updates used battery pack power in warehouse after each swapping task (set to depleted battery' s power). Equation (29) updates warehouse battery pack power at swapping start (product of time difference between current and previous swap end and charging rate). Equation (30) calculates swapping station waiting time (queue if previous AGV not finished; charging wait if selected pack below minimum power). Equation (31) limits initial total battery quantity in large/small stations to no more than total swapping times. Equation (32) calculates swapping position start time (arrival time plus queue time). Equation (33) calculates battery pack replacement completion time (swap start time plus operation duration). Equations (34) and (35) specify variable constraints.

3 Genetic Algorithm

The multi-AGV scheduling problem considering swapping processes and battery pack quantity is essentially similar to multi-cycle VRP problems, characterized by multi-loop operations, high concurrency, and susceptibility to local optima. Genetic algorithms are global optimization methods enabling high concurrency and global search with excellent convergence and robustness. Their flexible encoding supports both real-number and binary encoding, with simple effective rules generating fewer illegal solutions during genetic operations and population updates. Therefore, this paper employs genetic algorithms to obtain approximate optimal solutions.

3.1 Chromosome Encoding

This paper adopts real-number encoding for the genetic algorithm, which intuitively represents practical problems through chromosomes. As shown in Figure 3, a chromosome for the upper-level AGV container task scheduling model consists of two segments, each containing n genes where n represents the number of container tasks. The first n genes represent container task indices, and the latter n genes represent corresponding AGV indices. In the 2n genes, gene i (i n) indicates the container task number, executed by the AGV number represented by gene i+n.

The lower-level AGV swapping scheduling model uses similar chromosome encoding principles. As shown in Figure 4, the chromosome divides into two segments: the first segment' s gene values represent swapping station numbers (1 for small station, 2 for large station), with length equal to total swapping times generated by all AGVs in the upper model. The latter segment' s gene values represent battery pack numbers in the station. In Figure 4, the first genes in both segments indicate that for the first swapping demand among all AGV swapping needs, the task goes to the small station where the swapping robot selects battery pack No. 2.

3.2.1 Selection

Both upper and lower models employ roulette wheel selection operators with the following steps:
a) Calculate each individual' s fitness value Fm;

b) Calculate each individual' s probability Pm of being inherited to the next generation;
c) Compute each individual' s cumulative probability Cm;
d) Generate a random number s (0,1]; if Cm-1 < s Cm, select individual m;
e) Repeat step 4 until population size equals initial population size.

3.2.2 Crossover and Mutation

The upper model uses two-point crossover and two-point mutation. The crossover process selects two parent chromosomes M1 and M2, randomly chooses two crossover points r1 and r2, and exchanges chromosome segment p1 between r1 and r2 on M1 with segment p2 on M2, producing offspring m1 and m2. Due to different gene meanings in chromosome segments, cross-segment crossover is prohibited. Since one container can only be handled by one AGV, duplicate gene values after exchange must be updated to missing gene values in the chromosome. Figure 5 illustrates this process.

Two-point mutation randomly selects mutation positions q1 and q2 on both chromosome segments. Since the first segment represents container task numbers and the second represents AGV numbers (with one container per AGV), mutation performs container task number mutation and AGV index mutation at respective positions. Figure 6 shows this process.

The lower model uses similar crossover/mutation but employs single-point crossover and single-point mutation to preserve genetic characteristics due to smaller chromosome size.

3.3 Fitness Function

The bi-level model' s objectives are minimizing makespan and total swapping time. Decoding the chromosome, the last container task's completion time is the makespan. Swapping time equals the difference between swapping completion and demand generation times, comprising travel-to-station time, queue waiting time, battery charging wait time, and travel-to-subsequent-task time. Their reciprocals serve as fitness functions for upper and lower genetic algorithms.

4.1 Parameter Settings

To evaluate the bi-level model' s effectiveness, Matlab solves the following examples. A case with 100 containers and 5 AGVs is designed. Container task attributes (earliest start times, origins, destinations) are shown in Table 3. Population size NP=50, maximum iterations M=100. Upper-level crossover and mutation probabilities are pc=0.7 and pm=0.01; lower-level probabilities are PC=0.5 and PM=0.01. AGV swapping SOC threshold is 30%. AGV speeds vary by SOC: empty travel speed is 2.5 m/s when SOC (0,30%]; empty/loaded speeds are 3 m/s and 2.5 m/s when SOC [30%,60%]; and 4 m/s and 3 m/s when SOC [60%,100%]. Power consumption rates are 0.01% and 0.025% per meter for empty and loaded states, and 0.005% per second when parked. Two swapping stations (one large, one small) are located at both ends of AGV travel lanes, each with one swapping position. Station-yard-quay crane distances are in Table 4. Yard crane and quay crane operations take 90s and 120s respectively. Swapping robot operation rate is 300s per swap. The large station initially has 30 battery packs, the small station 15. The swapping strategy is "swap-while-charging" with minimum swappable power Pv=60%. Based on electric bus research, charging rate is 8 minutes of endurance per charging minute.

4.2 Small-Scale Bi-Level Model Results

With these parameters, the genetic algorithm solves the case. The upper model' s fitness convergence is shown in Figure 7, with results in Table 5. The approximate optimal solution shows a makespan of 167 minutes with only 1 swap occurring during AGV 3' s operation. The lower model results show this swap occurred at the small station using battery pack No. 4, with total swapping time of 10.4167 minutes. Figure 8' s Gantt chart for AGV 3 shows it executed 18 container tasks and 1 swapping task.

4.3 Large-Scale Bi-Level Model Results

After validating the bi-level model with the small case, the scale is expanded to 500 containers and 10 AGVs. The upper model outputs a makespan of 632.6 minutes with 13 total swaps across 10 AGVs. Table 6 shows AGV 3' s operation sequence, revealing swapping demands after tasks 77 and 1.

The lower model's fitness evolution is shown in Figure 9. Results show total AGV swapping time of 167.85 minutes, with each AGV' s swapping count, demand generation time, residual power, station, and battery pack number detailed in Table 7.

In this 500-container, 10-AGV case, 13 swapping demands occurred. Before optimization, 13 demands required 13 battery packs. After decision-making and constraints, battery pack usage records (Table 8) show 8 swaps at the small station and 5 at the large station. Battery packs 1, 2, 6, 20, 22, 38, 41, and 43 were used once; pack 7 twice; and pack 3 three times. Thus, optimization reduced required battery packs from 13 to 10—a 23.1% reduction.

The upper model improves battery pack utilization by considering loaded/unloaded power consumption differences and speed variations across SOC intervals. Statistical results (Figure 10) show swapping demands decreased from 14 to 13 times (one fewer swap). Average battery utilization increased from 61.34% to 67.80%, a 6.46% improvement.

4.4 Crossover Rate Sensitivity Analysis

Larger case scales affect chromosome length, and crossover rates impact results differently. Figure 11 shows AGV makespan varies with upper-level crossover rate pc, with optimal results at pc=0.6. Figure 12 shows total swapping time under different upper/lower crossover rates pc and PC, with optimal results at pc=0.6 and PC=0.5.

4.5 AGV Speed Sensitivity Analysis at Different Residual Power Levels

During AGV loading/unloading operations, actual terminal conditions cause speed variations across SOC levels. Research divides SOC into three intervals: forced charging (0,30%] (swapping only, empty speed only), opportunity charging [30%,60%] (both swapping and container tasks), and normal operation [60%,100%] (container tasks only) with higher speeds than opportunity charging. V0 and V1 represent empty and loaded speeds, which decrease with SOC. Excessive speeds accelerate power consumption, increasing swap frequency and contradicting makespan optimization. Table 9 presents five schemes for sensitivity analysis of empty/loaded speeds across SOC intervals to improve battery utilization.

Running each scheme 10 times and averaging results, Figure 13 shows Scheme 2 performs best: SOC [0,30%] with empty speed 2.5 m/s; SOC [30%,60%] with empty/loaded speeds 3 m/s and 2.5 m/s; SOC [60%,100%] with empty/loaded speeds 4 m/s and 3 m/s.

5 Conclusion

AGV efficiency significantly impacts automated container terminal performance. This paper addresses AGV loading/unloading operations considering battery endurance, loaded/unloaded SOC variation characteristics, and speed differences across residual power levels. For battery pack swapping processes, the paper considers swapping demand generation, battery pack selection principles, and processes, making decisions on station and battery pack selection for each demand. A bi-level model is established comprising an AGV container task scheduling model and a battery pack configuration model, solved using GA. A 500-container, 10-AGV example demonstrates the bi-level model effectively reduces total task completion time and total swapping time, improves AGV battery pack utilization by 6.46%, and rationally plans battery pack inventory, reducing quantity by 23.1%. This research provides practical significance for improving automated container terminal efficiency and offers insights for battery pack quantity planning in terminal swapping stations.

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Note: Figure translations are in progress. See original paper for figures.