A Spatiotemporal Perspective-Based Modeling and Optimization for Disassembly Line Balancing Problem of Waste Electric Bike Batteries

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Abstract. Aiming at complex time-space constraints, unbalanced workstation loads, prominent bottlenecks and low balance efficiency of waste electric bicycle battery disassembly lines, this paper constructs a multi-objective optimization model from the time-space perspective. Through field measurement, standard operation time of 17 disassembly processes is acquired, with constraints of sequence priority and hazardous waste spatial isolation defined. Taking minimum workstation quantity, smoothing index and time-space idle loss as optimization objectives, an improved genetic algorithm with constraint repair is applied to achieve optimal workstation allocation. Experimental results indicate that the line balance rate rises from 60.94% to 93.18%, the smoothing index drops from 51.76 to 8.97, time-space idle loss reduces by 84.27%, and hourly capacity improves by 51.32%. Bottlenecks are eliminated and hazardous processes satisfy isolation specifications. The proposed method effectively balances workstation workloads and enhances resource utilization, supporting lean improvement of disassembly production lines.

Keywords: Time-space perspective, Waste electric bicycle batteries, Disassembly line balance.

1 Introduction

The number of electric bicycles in China has grown rapidly, and a large number of 48V lead-acid batteries have reached their end-of-life. Waste batteries contain toxic materials and pose serious environmental risks, but also have high recycling value. Relevant policies require enterprises to establish standardized disassembly lines.

Waste battery disassembly is a typical Disassembly Line Balancing Problem (DLBP). Most small enterprises still use experience-based layout. Existing studies often ignore time-space coupling constraints, including process sequence, cycle time, workstation space, hazardous isolation, and material handling. This leads to bottlenecks, unbalanced workloads, low efficiency, and poor safety compliance.

This paper establishes a multi-objective optimization model from the time-space perspective. An improved genetic algorithm is designed to obtain the optimal workstation

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assignment. Experimental verification shows that the proposed method significantly improves line balance, productivity, and time-space resource utilization.

2 Analysis of the Disassembly Process and Time-space Constraints of Waste Electric Bicycle Batteries

2.1 Disassembly Process Flow and Operation Time for Each Step

The research object is the mainstream 48V12Ah waste lead-acid storage battery for electric bicycles. Through on-site process division, stopwatch time measurement and allowance coefficient correction, the whole process is divided into 17 indivisible basic disassembly processes, covering pre-processing, shell disassembly, waste liquid treatment, plate separation, material classification recovery and final warehousing. The process number, operation content, standard working hours, predecessor constraints and spatial attributes are shown in Table 1.

Table 1. Disassembly Process Schedule of Waste Storage Battery

Process No.	Operation Content	Standard Time Time/s	Predecessor Process Set	Spatial Operation Attribute
1	Waste battery sorting and appearance damage detection	26	None	Material temporary storage area
2	Shell dust removal and surface impurity cleaning	21	1	Front ordinary operation area
3	Removal of wiring terminals and connecting wires	33	2	Side operation space
4	Sealant stripping on battery shell	18	2	Narrow operation space
5	Destructive disassembly of battery upper cover	44	3,4	Special cover-opening space
6	Preliminary separation of internal separators	24	5	Internal cavity operation
7	Waste liquid drainage and closed collection of electrolyte	56	5	Independent hazardous waste isolation area
8	Overall extraction and transportation of plate group	31	6,7	Material transfer space
9	Separation of positive and negative plates	48	8	Partition disassembly workstation
10	Cleaning of separator fiber impurities	16	9	Small-part cleaning area
11	Surface impurity removal and polishing of lead plates	40	9	Heavy metal treatment area
12	Pretreatment of plate crushing	23	11	Equipment processing space
13	Classification of battery shell plastics	20	5	Ordinary material buffer area
14	Disassembly and recovery of waste wires	29	3	Offcut operation area
15	Weighing and registration of recycled materials	15	10,12,13,14	Terminal summary workstation
16	Packing of classified materials	22	15	Pre-warehousing area
17	Warehousing and transportation of finished materials	19	16	Warehousing conveying channel

2.2 Definition of Time-space Constraint System

Time Dimension Constraints: Processes strictly follow predecessor priority relations without reverse or skipping disassembly. The cumulative operation time of any workstation shall not exceed the production cycle CT. Processes are indivisible and cannot be operated in parallel. Minimum time intervals between adjacent processes are set to avoid operational safety risks.[1]

Space Dimension Constraints: Workstations own independent operating space. The hazardous electrolyte process is exclusively isolated and forbidden to combine with sorting, packaging and warehousing tasks. Layout is optimized to shorten transportation and avoid cross-contamination.[2]

Time-space Coupling Constraints: Longer workstation operation time leads to longer spatial occupation duration. Bottleneck processes simultaneously cause time congestion and spatial material accumulation. Handling time changes dynamically with workstation spacing, and Time-space losses are superimposed.

3 Mathematical Model Construction of Disassembly Line Balance Based on Time-Space Perspective

3.1 Model Parameter Definition

I= {1, 2, …,17}: Set of all disassembly processes; J= {1, 2, …, m}: Set of disassembly line workstations, m is the total number of workstations;t_i: Standard operation time of process i , unit: s; CT: Fixed production cycle of production line, unit: s;P_i: All predecessor constraint processes of process i; Decision variable:

$$x_{ij} = \begin{cases} 1, Process\ i\ is\ assigned\ to\ workstation\ j \\ 0, Process\ i\ is\ not\ assigned\ to\ workstation\ j \end{cases} \tag{1}$$

3.2 Constraint Conditions

Process Uniqueness Constraint: Each process is assigned to only one workstation without repetition or omission.

$$\textstyle\sum_{j=1}^{m} x_{ij} = 1, \forall_j \in I \tag{2}$$

Workstation Cycle Time Constraint: The total operation time of any workstation shall not exceed the production cycle.

$$\textstyle\sum_{i=1}^{17} t_i\, x_{ij} \leq CT, \forall_j \in J \tag{3}$$

Process Priority Constraint: If process $k \in P_i$, the assigned workstations satisfy:

$$j_k \leq j_i \tag{4}$$

The workstation number of predecessor process is not larger than that of subsequent process.

Spatial Isolation Hard Constraint: Process 7 can only occupy an exclusive isolated workstation and cannot be assigned with any other processes.

3.3 Multi-Objective Optimization Functions

Three-objective optimization model is established based on time-space perspective:
Objective 1: Minimize the number of workstations

$$mineZ_1 = m \tag{5}$$

Objective 2: Minimize line smoothing index SI to balance workstation load

$$mineZ_2 = SI = \sqrt{\sum_{j=1}^{m}(CT - \sum_{i=1}^{17} t_i\, x_{ij})} \tag{6}$$

Objective 3: Minimize total time-space idle loss of the whole production line

$$mineZ_3 = \sum_{j=1}^{m}(CT - \sum_{i=1}^{17} t_i\, x_{ij}) \tag{7}$$

4 Model Optimization Solution

4.1 Original Data and Problem Analysis

The original production line of the enterprise arranged workstations according to manual experience without considering time-space constraints. The original measured production cycle is CT=58s. The original workstation allocation, operation time and idle time of each workstation are shown in Table 2.

Table 2. Workstation Allocation and Working Hour Statistics of Original Disassembly Line

Workstation No.	Assigned Processes	Total Working Time/s	Idle Time/s	Spatial Attribute Description
1	1,2,	47	11	Slight idle
2	3,4	51	7	Normal load
3	5,	44	14	Moderate idle
4	6,8	55	3	Approaching bottleneck
5	9	48	10	Moderate idle
6	10,11	59	-1	Bottleneck workstation
7	12,13,14	42	16	Severe idle
8	15,16,17	50	8	Slight idle

Problems of Original Production Line:

1. Workstation 6 is the core bottleneck with overtime operation time, causing continuous congestion of the production line.

2. Workstation 7 has enormous idle loss, resulting in serious waste of personnel, equipment and space resources. Process 7 (electrolyte treatment) is not spatially isolated and mixed with other processes, bringing high safety compliance risks.
3. Process allocation ignores time-space constraints of transportation, leading to redundant material flow paths and large waiting loss. The workstation load fluctuates drastically with low balance rate, restricting overall disassembly capacity.

4.2 Design of Improved Genetic Algorithm

Aiming at the characteristics of time-space hard constraints, multi-objective optimization and process priority topology of waste battery disassembly, the traditional genetic algorithm is fully improved with a constraint repair module to guarantee the validity of solutions.

Integer workstation encoding is employed. The chromosome length is 17, with each gene denoting a process's workstation. Process, spatial, and cycle constraints are automatically verified in decoding.[3] Legal initial solutions are generated in batches based on process topology and hazardous waste spatial constraints; invalid allocations are directly eliminated to enhance initial solution quality.[4]

Weighted comprehensive evaluation integrating three optimization objectives:

$$Fit = \omega_1 \frac{1}{m} + \omega_2 \frac{1}{SI} + \omega_3 \frac{1}{z_3} \tag{8}$$

Weight coefficients: $\omega 1=0.4$, $\omega 2=0.35$, $\omega 3=0.25$

These weights are obtained via the Analytic Hierarchy Process according to practical production priority: fewer workstations > load balance > time-space idle loss reduction.

Selection: Roulette wheel selection with elite preservation to retain the optimal individual of each generation. Crossover: Adaptive two-point crossover with crossover probability Pc=0.86. Mutation: Adaptive single-point mutation with mutation probability Pm=0.11.Time-space Constraint Repair Mechanism: Automatically verify sequence constraints, hazardous waste isolation constraints and cycle constraints after decoding, and correct illegal solutions in real time to ensure executability of on-site schemes.[5]

4.3 Optimization Results and Experimental Comparative Analysis

After algorithm convergence, all constraints including production cycle, process priority, hazardous waste spatial isolation and material time-space flow are fully satisfied. The optimized production cycle is adjusted to CT=54 s, and the optimal workstation allocation is shown in Table 3.

Time dimension: Cycle time is shortened, bottlenecks are eliminated, workstation time is balanced, and idle loss is reduced. Space dimension: Hazardous electrolyte processes are independently isolated, layout is standardized, and material handling is optimized. Time-space coupling: Time congestion and space backlog are solved simultaneously, and resource utilization and productivity are greatly improved.

Table 3. Optimal Workstation Allocation Scheme of Optimized Disassembly Line

Workstation.	Assigned Processes	Total Working	Idle Ti	Spatial Attribute Description
1	1,2,4	45	9	Front preprocessing area
2	3,14	42	12	Side terminal disassembly area
3	5,6	48	6	Battery cover opening area
4	7	54	0	Exclusive isolated hazardous waste workstation (electrolyte dedicated)
5	8,9	49	5	Plate disassembly and transfer area
6	10,11	53	1	Plate cleaning area
7	12,13,15,16,17	52	2	Material collection and warehousing area

5 Conclusion

This paper studies the disassembly line balancing of waste electric bicycle batteries under time-space constraints and constructs a multi-objective optimization model. Experimental results show that the optimized production line has fewer workstations, shorter cycle time and eliminated bottlenecks, with greatly improved balance rate, productivity and time-space resource utilization. Electrolyte hazardous processes are independently isolated to satisfy safety requirements. The proposed model and algorithm effectively balance workstation loads and provide a practical approach for lean upgrading of battery disassembly lines.

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