

Production Line Balancing Optimization for Wire Harness Assembly Engineering

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Abstract

The rapid development of manufacturing has driven expansion in the automotive industry, placing wire harness manufacturers under dual pressure to enhance production efficiency and reduce costs. Addressing the challenges of low efficiency, uneven production rhythms, and prominent bottlenecks in wire harness assembly operations, this paper proposes a production line balancing method integrating industrial engineering theory with practical application techniques: Design and implement a Python-programmed wire navigation system to streamline wire positioning; Conduct 3D modeling of workstations to optimize layout and task area allocation; Evaluate the effectiveness of the optimization plan using metrics such as production line balancing rate and task duration. This research advances production line balancing in assembly engineering and offers practical reference value for the automotive wire harness manufacturing industry.

Keywords

Wire Harness Processing; Assembly Engineering; Industrial Engineering; Production Line Balancing; Bottleneck Processes.

1. Introduction

With the rapid development of manufacturing, particularly in the automotive industry, wiring harnesses play a crucial role as a core component of vehicle electrical systems. Their function is to connect various electrical devices within a vehicle, transmitting both electrical power and signals [1]. In recent years, driven by technological advancements and shifting market demands, improving production processes [2], eliminating bottlenecks, and enhancing overall production line efficiency have become pressing challenges for the assembly engineering [3].

Innovations and improvements in processing equipment continuously drive progress within the harness industry [4]. These include manufacturing lightweight harnesses using new materials [5]. VeSys Harness [6] for soft creation of 2D harness drawings and wire length calculations. JVelia [7] designed workstation area allocation to enhance secondary processing efficiency. Roser et al. [8] introduced the concept of equipment active time to identify bottlenecks. Aleksandr [9] addressed the relationship between processing constraints and production tasks through task and route allocation. et al. And intelligent tools that significantly enhance harness production [10], such as information collection and analysis systems [11], harness quality inspection management systems [12], [13], automatic terminal feeding systems [14], and visual information management systems [15]. Production line balancing is crucial across all industries [16]. Gao Jingjing [17] applied “5W1H” and “ECRS” to overcome bottleneck processes and optimize production line layout; Zhang Cuizhu et al. [18] constructed a mixed-integer programming model to solve production line balancing problems.

Jiao Yuling [19] established a bilateral U-shaped assembly line balancing collaborative optimization model to simplify assembly line balancing issues.

This paper proposes an optimization scheme for wire harness production based on industrial engineering theory and specific application domain techniques. The structure is as follows: Chapter 1 outlines the research background, significance, and objectives; Chapter 2 introduces the methodology; Chapter 3 analyzes the current state of wire harness processing and assembly operations; Chapter 4 presents improvement proposals and evaluates their effectiveness; Chapter 5 summarizes the findings and explores future research directions.

2. Research Methods

Industrial engineering is a discipline dedicated to enhancing the efficiency of production systems, processes, and operations through systematic analysis and optimization techniques. Its core objective is to maximize the effectiveness of production systems by implementing measures such as rational resource allocation, work design, and production scheduling.

The 5W1H questioning technique is a systematic approach for analyzing and solving problems. By systematically posing questions across six dimensions-What, Why, When, Where, Who, and How-it helps analysts gain deep insight into the underlying causes of phenomena and identify the most appropriate solutions.

The ECRS principle is one of the core tenets in industrial engineering, widely applied in workflow improvement. It specifically encompasses: Eliminate (whether an activity can be omitted), Combine (whether multiple processes can be merged), Rearrange (whether sequences can be swapped), and Simplify (whether procedures can be streamlined). This principle can be applied to analyze any task, process, action, layout, time, or location, fostering new concepts and methods that integrate people, materials, and spaces.

When conducting production line balancing analysis using data, data preprocessing is required to determine normal time and ultimately establish standard time [20]. The steps for stopwatch time studies are as follows: First, determine the number of observations. Then proceed to the production site to observe and record data. Subsequently, process and calculate the data, inspect, analyze, and eliminate outliers within the observed values, and finally calculate the average.

Production line balancing, also known as bottleneck improvement, aims to reduce time waste by optimizing bottleneck processes. This ensures that the operation time at each workstation is essentially the same, balancing the processing time between stations. Ultimately, it achieves the goals of increasing production efficiency, reducing labor costs, and minimizing waste [21].

Takt time refers to the interval required for an operator to complete a specific process on the production line. The bottleneck is the slowest link in the production process, while a process constitutes the fundamental unit of production activity [22]. Standard time denotes the duration required for a proficient operator to complete a task under suitable working conditions, using specified tools and adhering to standard operating procedures [23]. The production line balance rate is calculated as the ratio of the sum of operation times at each workstation to the product of the number of workstations and the production cycle time.

In fields such as production process optimization and task scheduling, traversal and recursive algorithms are highly effective programming methods [24]. A traversal algorithm sequentially accesses each element in a data structure according to specific rules. Through traversal, operations like searching, sorting, and counting can be performed on data. In production process optimization, traversal algorithms are frequently employed to address task allocation and production line scheduling problems. Recursive algorithms solve problems by decomposing them into smaller subproblems and calling themselves to resolve these subproblems. Recursion typically consists of two parts: the base case and the recursive step. The base case defines the termination condition for

recursion, while the recursive step decomposes the original problem into smaller subproblems, solving them incrementally through recursive calls [25].

3. Research Status

3.1 Research Status of Equipment

All processes of the harness assembly project under study are performed on a single workbench, which remains fixed in position. Opposite the workbench lies the material zone, where materials and tools are stored. The layout consists of five workbenches paired with one material zone. Each workbench primarily comprises two components: the assembly panel and the processing frame beneath it.

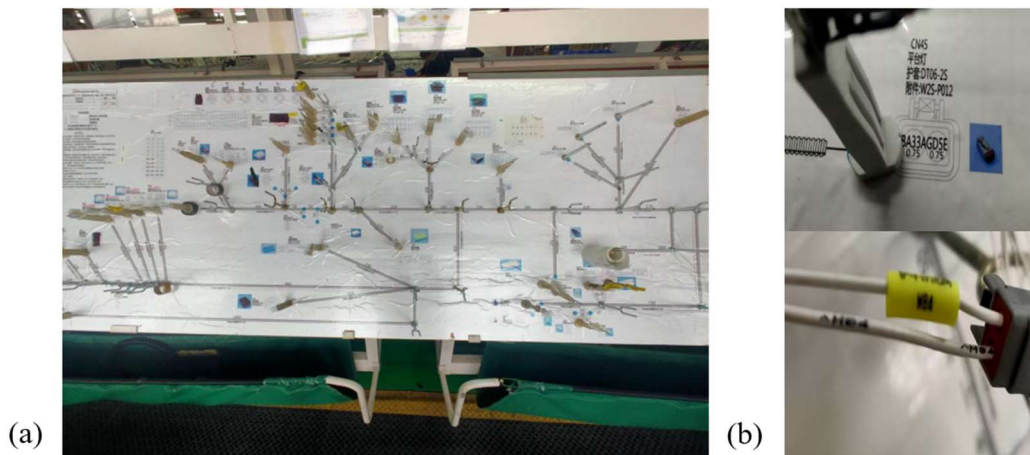


Fig. 1 (a) Assembly Engineering Workbench; (b) Connector Markings and Wire Markings

Automotive wiring harness drawings provide detailed specifications including harness length, routing paths, connection methods, classification, material composition, wire gauge, component types, and specifications. Wire markings must indicate wire model, color, and gauge. Wire model identification is not limited to connector markings. During assembly, ensure wire models match connector markings.

3.2 Research Status of Workflow

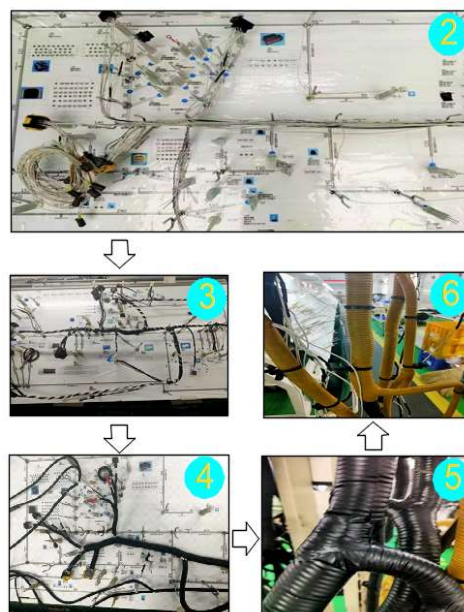


Fig. 2 Assembly Engineering Drawing

The assembly engineering drawing outlines the steps involved, such as wire handling, assembly, and reinforcement, leading to the final wire harness product. This assembly process can be broken down into seven steps: wire handling, wire assembly, harness reinforcement, rubber tubing installation, rubber tubing reinforcement, cable tie placement, harness storage.

The workflow is as follows: Operators transport wires awaiting processing from the material area to the workbench; position and secure wires on the assembly board according to the wiring harness diagram; reinforce assembled wires using materials such as tape or rubber tubing; install cable ties on the assembled harness per diagram specifications and perform finishing adjustments; after completing all assembly tasks, conduct quality inspections to ensure electrical continuity and dimensional compliance; finally, proceed with packaging and storage.

When studying assembly line production processes, each operation element within every process step is segmented and categorized. Stopwatch timing methods are employed to measure task durations, and the obtained data is processed. Finally, through calculation, the standard operation times for each process step in the assembly operation are derived.

Calculations show that the current production line balance rate for the assembly process is 62.06%. The primary bottleneck is identified in Process 2, while the operation times for Process 1 and Process 7 are significantly below the production cycle time.

3.3 Problem Analysis

Through analyzing the current state of wire harness assembly operations, several critical issues were identified, and their root causes were further explored:

(1) Inefficient workflow: The layout of workstations and material zones is unreasonable, with fixed configurations and limited space. This forces operators to frequently move wires and tools, resulting in wasted time. (2) Excessive manual labor: Production remains highly dependent on manual operations, particularly during wire routing and positioning. Workers must manually locate wires based on drawings, increasing the risk of operational errors and fatigue. (3) Bottleneck processes causing production stagnation: Tasks like wire routing and reinforcement within assembly engineering involve lengthy operation times and inefficient process design. This increases workload intensity and duration, creating production line imbalances that undermine overall efficiency. (4) Uneven task distribution: Imbalanced assignment of production line tasks, with excessive duration in certain processes, leads to overburdened workstations and reduced overall line efficiency.

4. Improvement Measures

4.1 Route Navigation System Design

To address bottlenecks in wire installation and positioning on existing production lines, this paper designs a Python-based wire navigation system. The workflow is as follows: Operators input the wire model. Based on the input model, the system determines whether the wire exists. If it does not exist, a pop-up window displays: "This wire does not exist. Please re-enter." If the wire exists, the system locates all segments within that circuit and renders the route. Upon clicking "Query," the input field automatically resets, enabling operators to query subsequent wires.

Key design modules include: Data Entry Module: Records wire model numbers and corresponding circuit information, including wire length, path, and connector types. Query Module: Retrieves circuit details from the database based on wire model input, displaying wire paths and connection points. Display Module: Presents circuit diagrams via a graphical interface, enabling workers to visually understand wire locations and paths to minimize operational errors.

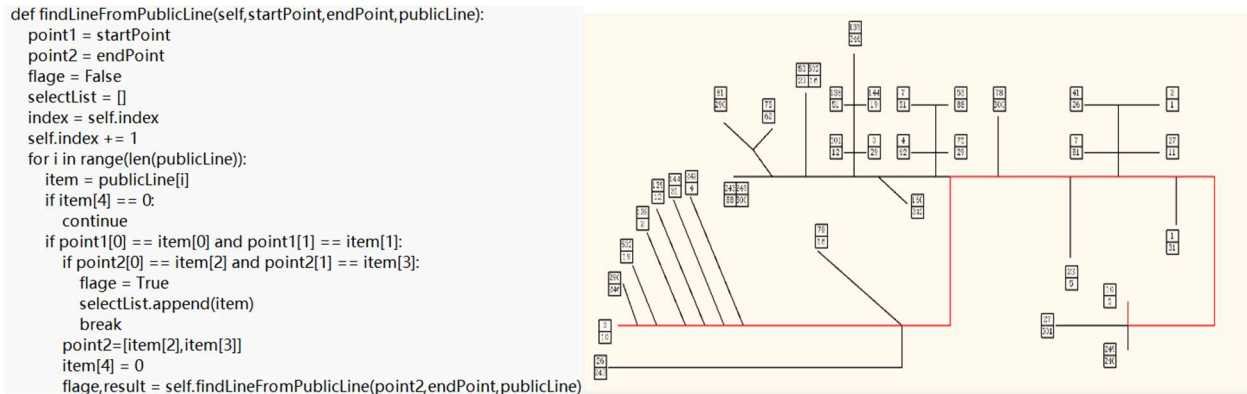


Fig. 3 Line Navigation System: (a) Navigation part code; (b) Line navigation demonstration

4.2 Workbench Design

To address the issue of an inefficient existing workbench layout, a 3D model of the workbench was created, and an improvement plan was proposed. First, the dimensions of the existing workbench—including length, width, and height—were measured to serve as the foundation for the redesign. Based on production requirements and workflow processes, the layout of workstations, material zones, and the workbench itself was optimized to ensure smoother operations. The improved workbench was visualized through 3D modeling and further adjusted to guarantee rational tool and process placement alongside user-friendly operation.

The original fixed workbench was redesigned into an integrated “adjustable processing frame + cart + conveyor belt” system. Adjustable Processing Frame: The workbench features an adjustable frame to modify its angle according to different operational requirements, enhancing operator comfort. Optimized Material Storage Zone: The material zone was optimized based on usage frequency, placing frequently used materials near the workbench to reduce material retrieval time for operators. Conveyor System: Install conveyor devices around the workbench to facilitate rapid movement of wires and finished harnesses, reducing manual handling time and labor expenditure.

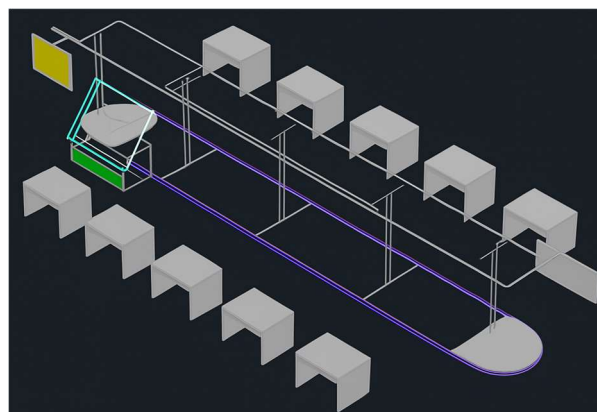


Fig. 4 Overall effect drawing of the workbench

4.3 Evaluation of Measures

The introduction of the line navigation system significantly reduced the operation time for the bottleneck process of “wire installation.” Operators can quickly query and accurately locate wire positions through the system, cutting wire installation time from 6 seconds to 3 seconds and reducing overall operation time from 468 seconds to 342 seconds. This measure effectively eliminated the production line bottleneck and enhanced overall operational efficiency. Following the implementation of workstation optimization and the wire routing navigation system, a balance analysis was conducted on the improved production line. The line balance rate increased from 62.06%

to 87.49%, with total production time reduced by 180 seconds. These results validate the feasibility of the improvement measures.

Operation	Operation Content	Work Element	Element Content	Standard Time(s)	
				Work Element	Operation
1	Transport Wires	1	Transport wires	32	117
		2	Install assembly board	85	
2	Set Up Wires	3	Take wires	54	468
		4	Position wires	216	
		5	Place wires	198	
3	Reinforce Wire Harness	6	Take tape	2	354
		7	Wrap wire harness	350	
		8	Place tape	2	
4	Sleeve Rubber Tube	9	Take rubber tube	90	378
		10	Select appropriate position	76.5	
		11	Sleeve rubber tube	211.5	
5	Reinforce Rubber Tube	12	Take tape	2	319
		13	Wrap rubber tube	315	
		14	Place tape	2	
6	Install Cable Ties	15	Take cable ties	48	272
		16	Fasten cable ties	128	
		17	Trim cable ties	96	
7	Store Wire Harness	18	Store wire harness	40	125
		19	Remove assembly board	85	

Operation	Operation Content	Work Element	Element Content	Standard Time(s)	
				Work Element	Operation
1	Process Connection	1	Store Wire Harness	40	245
		2	Remove Assembly Board	85	
		3	Move Workbench	3	
		4	Transport Wires	32	
		5	Install Assembly Board	85	
2	Set Up Wires	6	Take Wires	36	342
		7	Position Wires	108	
		8	Place Wires	198	
3	Reinforce Wire Harness	9	Move Workbench	3	353
		10	Wrap Wire Harness	350	
4	Sleeve Rubber Tube	11	Move Workbench	3	336
		12	Take Rubber Tube	45	
		13	Select Position	76.5	
		14	Sleeve Rubber Tube	211.5	
5	Reinforce Rubber Tube	15	Move Workbench	3	318
		16	Wrap Rubber Tube	315	
6	Install Cable Ties	17	Move Workbench	3	259
		18	Take Cable Ties	32	
		19	Fasten Cable Ties	128	
		20	Trim Cable Ties	96	

Fig. 5 (a) Original standard operating hours; (b) Improved standard operating hours

5. Conclusion

With the intensifying global competition in manufacturing, enhancing production efficiency and reducing costs have become critical challenges for many enterprises. This paper focuses on wire harness assembly engineering and achieves the following objectives: (1) Intelligent Production Guidance: By designing and implementing a wire navigation system, the wire routing and positioning processes were optimized, significantly reducing operation time in bottleneck processes. (2) Workstation Layout Optimization: Three-dimensional modeling improved workstation arrangements, ensuring more rational operational space and reducing unnecessary movements and time wastage. (3) Data-driven analysis: Through rational task allocation and sequence adjustments, the production line's balance rate increased from 62.06% to 87.49%, significantly boosting productivity. Future enhancements can be achieved by integrating artificial intelligence, IoT technologies, and big data analytics to optimize the entire production line for more efficient management.

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