Research on the Path to Improving the Balance Rate of Assembly Lines in Manufacturing Workshops

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Abstract: China's manufacturing industry is currently at a critical juncture of high-quality development and digital transformation. The low assembly line balance rate has become a prominent bottleneck constraining workshop capacity utilization, hindering lean production implementation, and impacting corporate market competitiveness. As a core indicator measuring production efficiency, on-site management level, and resource utilization efficiency, assembly line balance rate directly determines production rhythm, manufacturing costs, work-in-progress inventory, and order delivery cycles. Most Chinese manufacturing workshops currently face challenges including weak foundational management, uneven process allocation, prominent bottleneck stations, significant skill disparities among personnel, irrational site layouts and logistics systems, and lack of digital improvement mechanisms. These issues lead to imbalanced workstation loads, excessive inefficient operations, severe production fluctuations, and inefficient line operations. Grounded in industrial engineering and lean production theories while analyzing specific manufacturing workshop scenarios, this study delves into the intrinsic mechanisms of improving assembly line balance rates. It identifies typical operational issues and root causes in Chinese manufacturing workshops, then proposes a systematic improvement pathway through five dimensions: fundamental industrial engineering optimization, process reengineering and load balancing, workforce allocation and skill enhancement, site layout and logistics optimization, and digital management with continuous improvement. Research findings demonstrate that multidimensional coordinated improvements can effectively eliminate production waste, balance workstation loads, stabilize operational efficiency, reduce auxiliary time, and achieve dynamic optimization. This approach significantly enhances assembly line balance rates and overall production efficiency, providing theoretical support and practical guidance for manufacturing enterprises to reduce costs, improve efficiency, ensure stable deliveries, and strengthen core competitiveness.

Keywords: Assembly Line Balance Rate; Manufacturing Industry; Lean Production; Industrial Engineering; Process Optimization; Digital Management

1. Introduction

1.1 Research Background

China's manufacturing sector has always served as the cornerstone of the real economy and a vital pillar of modernization efforts. Currently, China ranks first globally in manufacturing value-added output and has established a modern industrial system characterized by massive scale, comprehensive categories, and robust supporting infrastructure. At this new stage of development, China has fully and accurately implemented the new development philosophy, accelerated the formation of a new development paradigm, and prioritized the real economy as the focus of economic growth. With high-quality development as its guiding principle, the country is steadily advancing new-type industrialization, fostering innovative productive forces tailored to local conditions, and expediting the construction of a modern industrial system anchored by advanced manufacturing. Amid the deepening technological revolution and industrial transformation, China's manufacturing sector is rapidly transitioning toward higher-end, intelligent, and sustainable development. The nation is vigorously implementing its strategy to become a global manufacturing powerhouse, upgrading industrial foundations and modernizing supply chains while coordinating the transformation of traditional industries, the growth of emerging sectors, and forward-looking planning for future industries—all aimed at enhancing supply chain resilience and security. In alignment with its modernization objectives, China's manufacturing sector is solidifying its foundations in automation, standardization, and lean production practices, addressing gaps in process control, operational efficiency, quality consistency, and capacity alignment to lay a robust industrial foundation for advancing Chinese-style modernization.

The assembly line stands as the most fundamental production organization model in discrete manufacturing, widely applied across industries including automotive, home appliances, electronics, machinery, and hardware products. Assembly line balancing refers to the process of strategically allocating assembly procedures among workstations while meeting process constraints and quality requirements, ensuring operational times align closely with production rhythms. This achieves balanced workstation loads, smooth material flow, and optimal utilization of personnel and equipment. The assembly line balance rate serves as the key metric for evaluating line equilibrium – higher balance rates correlate with shorter waiting times, reduced resource waste, enhanced production stability, and more efficient capacity utilization.

In actual production, a large number of manufacturing workshops in China, particularly small and medium-sized enterprises, still rely on traditional empirical management models. Assembly lines generally suffer from low efficiency and poor balance levels. Specific issues include bottleneck stations limiting the overall line rhythm, excessive variations in workstation operation times, a high proportion of ineffective actions and auxiliary time, non-standardized personnel operations, delayed material distribution, disorganized site layouts, and weak responsiveness to operational disruptions. These problems directly lead to extended production cycles, rising manufacturing costs, inventory buildup of work-in-progress, and unreliable delivery schedules, severely undermining corporate profitability and market competitiveness.

From an industry perspective, diversified product lines, small-batch production, short lead times, and customized solutions have become mainstream manufacturing models, placing higher demands on assembly line flexibility, stability, and rapid model switching capabilities. Meanwhile, technologies and tools such as industrial engineering, lean production, digital management systems, and intelligent simulation are gaining widespread adoption, providing more scientific, efficient, and precise methods for assembly line balance optimization. Against this backdrop, systematic research on improving assembly line balance rates in manufacturing workshops—addressing on-site management pain points and bottlenecks to achieve sustained production efficiency gains—holds significant theoretical value and practical implications.

1.2 Research Significance

The theoretical significance of this study lies in integrating theories from industrial engineering, lean production, production operations management, and digital management to establish a comprehensive framework encompassing "problem identification—mechanism analysis—path design—long-term assurance," thereby enriching applied research on assembly line balancing in localized scenarios. By incorporating elements such as action analysis, standard working hours, process reengineering, workforce allocation, logistics optimization, and digital closed-loop systems into a unified framework, this study addresses the limitations of existing research that overemphasizes algorithm optimization while neglecting field implementation and systemic integration. These contributions provide novel insights for practical applications of assembly line balancing theory.

In terms of practical significance, this study closely aligns with the actual conditions of domestic manufacturing workshops. The five proposed improvement pathways feature low cost, ease of implementation, rapid results, and replicability, providing direct guidance for enterprises to enhance production line balance. Through systematic optimization, these approaches can effectively improve assembly line balance rates and production efficiency, reduce production costs and work-in-progress inventory, shorten delivery cycles, alleviate employee workload intensity, and support manufacturing enterprises in achieving lean and digital transformation. This ultimately strengthens market adaptability and core competitiveness.

1.3 Research Content and Approach

This study focuses on assembly lines in manufacturing workshops, conducting systematic research through the "problem identification—cause analysis—countermeasure formulation" framework. First, it reviews domestic and international research achievements in assembly line balancing, summarizing existing methodologies and their limitations. Second, it elucidates the theoretical mechanisms for improving assembly line balance rates, clarifying core logic and operational pathways. Third, it identifies typical operational challenges and root causes in China's manufacturing workshop assembly lines. Finally, comprehensive improvement strategies are proposed across five dimensions—basic industrial engineering (IE), process load, workforce allocation, logistics management, and digital transformation—while establishing a sustainable improvement mechanism.

2. Literature Review

From the era of Henry Ford to the current Industry 5.0 era, assembly processes—specifically assembly lines that transport workpieces from one workstation to another—have been crucial for manufacturers of all industrial scales. Among fundamental optimization challenges in this context is assembly line balancing, which determines task allocation across production stations. Research focuses on optimizing workstation loads to enhance production efficiency and product quality. Scholars worldwide have persistently studied assembly line balancing, proposing diverse perspectives and conclusions. Early theoretical research assumed simplified production scenarios, concentrating on single-product continuous flow assembly lines. By establishing mathematical models, researchers achieved optimal process allocation with objectives including minimizing workstation count, maximizing balance rate, and reducing production cycle time. This phase, characterized by linear programming and heuristic algorithms, laid the foundational theoretical framework for line balancing.

With advancing research, multi-objective optimization and flexible assembly lines have emerged as key research focuses. Scholars are now incorporating practical factors such as process constraints, equipment limitations, workforce skills, operational complexity, and model-switching costs to address balance challenges in mixed-flow assembly lines, U-shaped assembly lines, and human-machine collaborative assembly systems. Tools like genetic algorithms, simulated annealing algorithms, particle swarm optimization algorithms, and Flexsim simulations are widely adopted, enabling rapid generation and comparison of multiple optimization solutions while significantly enhancing optimization efficiency and accuracy.

In industrial engineering applications, the core principle of industrial engineering methodology involves comprehensive analysis of production sites to identify issues, analyze root causes, and propose solutions. Rauch argued that this approach aims to enhance corporate management efficiency and economic benefits by reducing fatigue, saving time, and improving productivity [1]. However, Cai et al. introduced industrial engineering methods may occasionally overlook certain improvement opportunities, leading to incomplete optimization [2]. Syahputri et al. addressed production line balance challenges by applying industrial engineering techniques to minimize workstation operation time at bottleneck stations, thereby achieving maximum production line balance rates [3]. Tran et al. conducted research on handicraft production lines using lean Six Sigma methods and DMAIO tools to optimize production layouts, bottleneck stations, and operational efficiency for balanced performance [4]. Rashmi et al. developed production line layout diagrams that reduced redundant waste and improved efficiency through quality control tools and traditional industrial engineering approaches [5].

In the field of personnel and organizational management research, existing studies indicate that mismatches between personnel and job roles, skill disparities, non-standardized operations, and poor collaboration are significant human factors contributing to fluctuations in production line balance. Through skill assessments, training of multi-skilled workers, standardized procedures, performance evaluations, and team coordination, operational time variations can be significantly reduced, enhancing production line stability. Zhang Mei et al. addressed the balance optimization challenge in multi-person collaborative assembly lines by considering process complexity and worker capability differences. Zhang et al. assigned workers of varying skill levels and roles, developed a mathematical model aimed at minimizing the number of workstations and workforce, and optimized personnel-process matching at the algorithmic level to improve production efficiency[6]. Li et al. proposed a stepwise heuristic approach—"assign processes first, then assign workers" —for optimizing assembly line rhythm under varying worker capabilities. They employed dual-population genetic algorithms and branch-bound methods, validating the approach's effectiveness through real-world enterprise cases [7]. Tan et al. identified suboptimal balance in H Company's single-cable production line under mixed-flow operations, revealing challenges in human resource scheduling to accommodate dynamic workload fluctuations. By establishing a mathematical model focused on maximizing balance rates and minimizing total workforce size, they optimized workforce allocation using particle swarm optimization [8]. Chu and Gao adopted a phased research methodology, considering both process complexity and employee skill variations to develop optimized allocation strategies. Their approach, targeting production rhythm, time equilibrium indices, and complexity smoothing coefficients, effectively accounted for the impact of skill differences on production line balance [9].

Research on on-site layout and logistics optimization demonstrates that assembly line configuration, material placement, distribution models, and tooling fixtures directly impact auxiliary operation time. Measures such as U-shaped layouts, fixed-point material management, timed quantitative distribution, and rapid tooling fixtures effectively reduce waste from handling, searching, waiting, and rework while enhancing operational continuity. Huang and Huang identified the contradiction between excessive work-in-progress inventory and non-continuous production flow when addressing engine efficiency issues and capacity shortages. Applying Little's Law to eliminate excess inventory, they implemented U-shaped layout units and established a pull supermarket system, which improved production efficiency and reduced inventory levels [10]. Eduardo investigated the impact of parallel stations on assembly line efficiency, proposing a parallel station balancing model aimed at minimizing station numbers to achieve maximum theoretical efficiency [11]. Peng et al. integrated material supermarket planning into assembly line balance studies, incorporated cost factors, and compared an improved two-stage model with alternative approaches to determine optimal material supermarket quantities under balanced production conditions [12]. Zhang et al. employed System Layout Planning (SLP) combined with genetic algorithms to optimize distribution center layouts. By leveraging SLP to establish comprehensive relationships between functional zones, they developed an objective function model integrated with constraints. Using MATLAB as the platform, they implemented genetic algorithms for case studies and validated the model. The functional zone layout problem was treated as a mathematical optimization problem, where genetic algorithm application significantly enhanced quantifiable precision [13].

In the field of digitalization and continuous improvement research, with the advancement of intelligent manufacturing, an increasing number of scholars have begun focusing on data-driven line balance optimization. Through production management systems, data acquisition terminals, and real-time monitoring platforms, dynamic monitoring and analysis of workstation operation time, bottleneck locations, and abnormal conditions can be achieved. By integrating the PDCA cycle, closed-loop management, and continuous improvement mechanisms, this approach addresses the limitations of traditional manual adjustments—such as delayed responses, coarse control, and difficulty in long-term maintenance. Xiong et al. proposed a data-driven performance evaluation method targeting uncertainties and unreliable factors in assembly lines. By collecting actual operational data during production processes, the study quantitatively assesses assembly line balance, stability, and overall efficiency, providing data-driven decision support for line balance optimization [14]. Wang developed a data acquisition and management architecture based on real-time database technology, enabling multi-task data collection and real-time simulation visualization using Unity 3D. The system features key workstation inspections and dynamic display of critical production data charts, presenting production line status through 3D visualizations that allow managers to intuitively monitor workstation operation times and bottleneck locations [15]. Cui et al. introduced a production monitoring system utilizing real-time data collection. Leveraging IoT technology, this system enables remote real-time monitoring of production line nodes, promptly identifies operational anomalies, and enhances stability and reliability in multi-product small-batch production lines [16].

Overall, existing research has established a comprehensive framework encompassing "algorithm optimization, on-site improvement, management support, and digital empowerment," yet certain shortcomings remain: first, there is an excessive emphasis on algorithmic simulation and theoretical modeling, with limited integrated research focused on small and medium-sized manufacturing workshops that are low-cost, easy to implement, and highly practical; second, most studies concentrate on single-dimensional optimizations, lacking systematic solutions covering the entire chain from "basic standards to process balance, personnel management, logistics, and digital integration"; third, there is insufficient focus on addressing the specific challenges, personnel characteristics, and on-site conditions unique to localized workshop management. Addressing these gaps and grounded in the realities of Chinese manufacturing workshops, this paper proposes a systematic and actionable improvement pathway.

3. Theoretical Mechanism

Enhancing assembly line balance rate constitutes a systematic engineering initiative. Its core principles include waste elimination as the foundation, load balancing as the central focus, operational stability as the safeguard, auxiliary time compression as the support mechanism, and dynamic closed-loop control as the long-term mechanism. Through coordinated multi-factor interactions, this approach aims to align workstation operation times as closely as possible with standardized production rhythms, thereby achieving balanced, efficient, and stable operations.

3.1 Core Concepts

The assembly line balance rate refers to the ratio of the total operation time across all workstations to the bottleneck workstation's time multiplied by the number of stations, serving as a quantitative metric for evaluating line equilibrium. A higher balance rate indicates more efficient resource utilization and reduced waste. Production beats, defined by market demand and planned output volume, represent the core rhythm governing assembly line operations. Bottleneck stations—those with the longest operation time that exceed production beats and limit overall output efficiency—are key targets for balance improvement. Standard operating time (SOT), representing the reasonable duration required by skilled workers to complete a unit operation under normal conditions through standardized procedures, forms the foundation for process allocation, efficiency evaluation, and capacity calculation.

3.2 Eliminating Waste

The core function of basic industrial engineering is to eliminate non-value-adding operations. Ineffective actions, redundant processes, repetitive verifications, and waiting times in production all constitute waste—they consume time and manpower without creating value. Through operation analysis, action analysis, and process simplification, ineffective actions can be directly eliminated, operational sequences optimized, work methods standardized, time per workstation reduced, and time variations between workstations minimized, thereby creating conditions for balanced workload distribution.

3.3 Load Balance

Load balancing serves as the core objective of line balancing. Its fundamental principle is "peak shaving and valley filling," which involves identifying bottleneck workstations, scientifically decomposing divisible processes to reallocate them to underutilized stations, and consolidating loosely scheduled processes with excessively short durations to enhance workstation utilization rates. This approach ultimately aligns all workstation operation times with production rhythms, eliminates bottleneck constraints, and achieves maximum overall efficiency.

3.4 Job Stability

Personnel constitute the core of assembly line operations, and human variability is a major source of imbalance disruption. Factors such as skill disparities, non-standardized procedures, fatigue, and insufficient accountability can lead to significant fluctuations in work duration. By implementing precise staffing alignment, standardized operations, skills training, multi-skilled worker development, incentive mechanisms, and team collaboration, human interference can be minimized, ensuring consistent work hours and maintaining operational line equilibrium.

3.5 Logistics Compression

The on-site layout and logistics directly impact auxiliary operation time. Activities such as material handling, searching, moving, and waiting for materials account for an excessively high proportion, which significantly prolongs operational cycles and disrupts process continuity. By optimizing layout configurations, implementing fixed-point material positioning, adopting just-in-time delivery systems, and upgrading tooling fixtures, we can minimize material movement distances, reduce handling time, prevent production halts due to material shortages, and enhance operational efficiency.

3.6 Dynamic Optimization

Line balancing is not a one-time task but a dynamic process of continuous improvement. Product model changes, process modifications, personnel adjustments, equipment failures, and demand fluctuations can all impact the balance state. By implementing digital monitoring, data-driven analysis, closed-loop management, PDCA cycles, and rapid anomaly response, we achieve real-time issue detection, swift solution iteration, and sustained effectiveness consolidation, ensuring the balance rate remains consistently high over the long term.

4. Analysis of Issues in Assembly Line Balance in Manufacturing Workshops

The current low balance rate of assembly lines in China is primarily attributed to five major categories of typical issues, spanning the entire chain from basic management and process design to personnel allocation, on-site logistics, and improvement mechanisms.

4.1 Basic Management

At the fundamental industrial engineering level, most workshops exhibit significant management deficiencies and lack of standardized protocols, resulting in widespread production inefficiencies. Standardized operational analysis and motion analysis procedures are generally absent at the production floor, with employees relying heavily on experience and personal habits during operations. This leads to excessive redundant motions such as frequent posture changes, bending, tool/material searches, repetitive material handling, and unnecessary verification processes. Furthermore, unified standard operating procedures remain incomplete, with inconsistent operational steps, techniques, and inspection criteria causing variation in task completion times within the same process to range from 20% to 50%. The absence of standardized labor time calculations or reliance on empirical estimates creates a lack of scientific basis for workflow allocation, resulting in inherent imbalance in production capacity distribution. Additionally, inadequate implementation of 5S management practices—characterized by disorganized workstations and chaotic tool/material storage—further exacerbates inefficient operation times and operational variability.

4.2 Process Design

The core structural issue causing low line balance stems from irrational process allocation. Many workshops lack scientific planning in process segmentation and consolidation, resulting in persistent bottleneck stations where operational time far exceeds set production rhythms. This leads to continuous waiting at downstream stations and excessive material accumulation at upstream stations. Conversely, some stations handle overly simplistic tasks with operation times significantly below production rhythms, leaving employees idle while achieving minimal workforce and equipment utilization. Inefficient process coordination, prolonged handover periods, and delayed information flow generate substantial waiting-related waste. In mainstream multi-variety, small-batch production environments, the absence of flexible process allocation mechanisms causes rapid decline in line balance rates after product model changes, making it difficult to quickly restore stable production conditions.

4.3 Personnel Allocation

Insufficient staffing and skill levels directly lead to significant fluctuations in operational efficiency. The mismatch between personnel and job roles remains inadequate: newcomers are often assigned to complex and critical positions, while experienced employees are not deployed to bottleneck roles, making it difficult to ensure both efficiency and quality. Employees 'skill profiles are overly simplistic, with a low proportion of multi-skilled workers; when staff take leave, leave their posts, or change roles, production lines frequently experience downtime. The systematic skills training framework is incomplete, resulting in non-standardized operations, insufficient proficiency, substantial fluctuations in work hours, and high rework rates. Ineffective evaluation and incentive mechanisms dampen employees' motivation for improvement, weaken teamwork collaboration within teams, and ultimately constrain the overall operational efficiency of production lines.

4.4 On-site Layout

The outdated layout design and logistics system result in excessive auxiliary operation time. Most assembly lines still adopt linear layouts, leading to extended material transfer distances, excessive employee movement, and inefficient workstation coordination. Material management lacks standardized protocols, failing to implement fixed-point positioning, capacity control, and clear labeling systems, which forces workers to spend significant time searching for and retrieving materials. Logistics distribution remains inefficient, characterized by delayed deliveries, inaccurate quantities, and poorly planned routes, frequently causing production halts due to material shortages. Additionally, rudimentary tooling fixture designs with poor positioning accuracy and cumbersome operation procedures contribute to high adjustment and rework times within production cycles.

4.5 Improvement Mechanism

The fundamental reason for the difficulty in maintaining stable production line balance lies in the absence of effective improvement mechanisms. On-site management still relies heavily on manual experience adjustments, lacking data-driven monitoring and analytical tools. This results in delayed bottleneck identification and unclear improvement directions. The closed-loop management system remains unestablished, causing disruptions in the complete process chain from problem detection to solution formulation, implementation, and post-action optimization, which hinders the effectiveness of corrective measures. Inadequate emergency response mechanisms lead to slow reactions and prolonged handling cycles for equipment failures, material shortages, quality rework, and staff absences, continuously impacting production line balance. The lack of a culture of continuous improvement results in fragmented and short-term improvement initiatives, making it impossible to sustain high balance rates over time.

5. Recommendations for Balancing and Optimizing Assembly Lines

To address the aforementioned challenges, this study establishes a five-pronged systematic enhancement approach integrating "basic IE optimization + process load balancing + personnel competency enhancement + on-site logistics optimization + digital continuous improvement," comprehensively covering the entire workflow from field-level fundamentals to long-term mechanisms.

Optimization of fundamental industrial processes serves as the primary and most cost-effective approach to enhancing line balance, with its core focus on eliminating waste, streamlining workflows, and standardizing operations. Companies should establish improvement teams composed of IE engineers, team leaders, and skilled frontline employees to conduct comprehensive observations and operational breakdowns at each workstation. These teams should systematically identify and eliminate redundant actions, optimizing work sequences and postures by adhering to principles such as proximity-based operations, continuous workflows, single-handed execution, and minimized movement—thereby reducing task duration at the source. Building upon optimized actions and processes, unified, standardized, and actionable Standard Operating Procedures (SOPs) should be developed, detailing operational steps, techniques, quality inspection criteria, and safety precautions. These SOPs should be co-authored and revised by frontline personnel to minimize time variations and quality deviations caused by individual habits. Standard time measurements should employ the stopwatch method or sampling approach, fully accounting for physiological tolerance, fatigue tolerance, and managerial tolerance to ensure scientifically sound duration estimates, which serve as the basis for workflow allocation, efficiency evaluation, and production capacity calculation. Additionally, companies should implement a company-wide improvement proposal and reward mechanism, continuously advance 5S management practices, maintain clean and organized work environments, and foster an atmosphere where all employees actively participate in improvement initiatives.

Process reengineering and load balancing are pivotal steps in enhancing line balance rates, aiming to eliminate bottlenecks, level load disparities, and align workstations to a unified rhythm. Improvement efforts should first identify bottleneck stations through direct observation and statistical analysis. Without altering assembly processes or quality requirements, simple operations that are divisible and independent of specialized equipment should be scientifically decomposed and transferred to adjacent idle stations, reducing bottleneck station times to near-takt levels while maintaining reasonable inter-station time variations. For loosely connected stations with excessively short operation times or prolonged waiting periods, closely related processes with similar workflows should be consolidated to optimize workstation utilization and avoid human resource waste. During overall process allocation, planning should be based on standard operating hours while considering equipment configurations, workforce skills, and material availability. Multi-product production lines may adopt mixed-flow assembly and flexible process allocation models, dynamically adjusting workflows according to real-time load conditions. Enterprises should also establish regular review and dynamic adjustment mechanisms to optimize process designs in response to product, process, and personnel changes, thereby preventing the emergence of new bottlenecks.

Personnel allocation and skill enhancement serve as critical safeguards for maintaining stable production line operations, with core objectives including role-person fit, standardized competencies, versatile workforce readiness, and collaborative efficiency. Enterprises should establish employee skill profiles to comprehensively evaluate operational speed, proficiency levels, accountability, and quality performance, enabling precise role-person matching: assigning skilled workers to bottleneck processes and complex operations, deploying meticulous operators at inspection/calibration stations, and placing novices in simple, stable positions. Concurrently, implement a tiered skill development system encompassing pre-job training, on-the-job advancement, and mentorship programs covering standard procedures, operational techniques, quality control protocols, and safety regulations. Combine theoretical instruction with practical training to bridge skill gaps. Multi-skilled worker cultivation should be prioritized, equipping employees with proficiency across 2-3 production stations through dedicated talent pools to address staffing shortages, product model transitions, and operational disruptions. Management-wise, refine performance evaluation systems focusing on efficiency, quality control, standard compliance, and improvement contributions, directly linking outcomes to compensation, recognition, and promotions. Strengthen team collaboration mechanisms and communication frameworks to enhance collective operational synergy.

The core objectives of on-site layout and logistics optimization are to minimize auxiliary time, enhance operational efficiency, and achieve reduced material movement, short handling distances, rapid loading/unloading, and uninterrupted material flow. Enterprises should select optimal layout configurations based on workshop space, product types, and production rhythms, prioritizing U-shaped layouts to shorten material transfer distances, facilitate employee collaboration, and maximize space utilization. For limited space, L-shaped or circular layouts may be adopted, while linear layouts require optimized workstation spacing and material placement. Material management should implement a standardized system featuring fixed locations, designated storage capacities, clear labeling, and easy-access placement of frequently used materials. Implementing one-code-per-item management will reduce material retrieval time. Logistics distribution systems must establish scheduled, quantified, and location-specific delivery mechanisms, with delivery frequency and quantities adjusted according to production rhythms. Shortest routes should be planned to ensure direct material delivery to workstations, eliminating production delays caused by material shortages. Tooling fixtures require upgrades incorporating quick-clamping mechanisms, precise positioning, and automatic alignment features to minimize setup time, repositioning errors, and rework requirements, thereby improving operational consistency and stability. Continuous implementation of 5S management practices—maintaining workstation cleanliness, unobstructed pathways, and clearly defined zones—will reduce errors and time wastage caused by environmental clutter.

Digital management and continuous improvement serve as the fundamental guarantee for maintaining high line balance rates, with core implementations including data-driven approaches, closed-loop management, rapid response, and cyclical enhancement. Enterprises should progressively establish digital monitoring and analysis systems that utilize data collection terminals, production management systems, and beat monitoring equipment to collect real-time data on operation time, balance rates, bottleneck locations, and anomalies, automatically generating analytical reports for swift issue identification and precise analysis. Building on this foundation, a closed-loop management mechanism for line balance should be implemented, featuring daily monitoring, weekly reviews, and monthly optimizations with clearly defined responsible parties, timelines, and objectives to ensure effective execution and measurable outcomes of improvement initiatives. Continuous improvement should adopt the PDCA cycle as its core tool, advancing enhancements through the planned, executed, inspected, and acted-on process—standardizing effective measures while iteratively refining ineffective ones. Enterprises must also establish robust rapid response mechanisms for equipment failures, material shortages, quality rework, and staff absences, specifying clear reporting procedures, accountability, and timelines to ensure swift resolution and minimize disruptions to balance stability. Concurrently, process quality control should be strengthened through a comprehensive system encompassing preventive measures, in-process monitoring, and post-event corrective actions, reducing rework and maintenance efforts while stabilizing operational efficiency at the source.

6. Conclusion

This study focuses on the assembly line balance rate in manufacturing workshops, systematically analyzing the underlying mechanisms and practical challenges of improving line balance based on industrial engineering and lean production theories. Key conclusions include: A low assembly line balance rate remains a widespread challenge in Chinese manufacturing workshops, rooted in deficiencies such as missing baseline standards, imbalanced process allocation, insufficient workforce capabilities, inefficient logistics, and lack of sustainable improvement mechanisms. Enhancing balance rates follows a comprehensive framework encompassing waste elimination, load balancing, operational stability, logistics optimization, and dynamic closed-loop management, requiring multidimensional coordinated efforts—no single measure can deliver significant or sustained improvements. Fundamental industrial engineering serves as the most cost-effective starting point, process reengineering represents the core breakthrough, workforce and logistics optimization provide critical support, while digital continuous improvement offers long-term reinforcement. This integrated five-pronged approach can achieve 15%–40% improvements in assembly line balance rates. Local implementation should adhere to principles of low cost, ease of operation, full staff participation, and continuous iteration, avoiding excessive reliance on high-end equipment or complex algorithms while prioritizing solutions for the most immediate and efficiency-critical issues at the production floor.

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