Research on Optimization of Manufacturing Workshop Facility Layout Based on Simulation and Genetic Algorithm

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Abstract: With the transformation of manufacturing to lean and intelligent, the rationality of workshop facility layout directly affects the logistics cost, equipment efficiency and production capacity of enterprises. Traditional layout methods rely on empirical decision-making, which is difficult to cope with core challenges such as heavy parts, complex process coordination, and frequent dynamic disturbances in complex manufacturing environments. This paper systematically sorts out the classification, constraints and objectives of workshop layout optimization problems, reviews the application status of intelligent algorithms such as genetic algorithms, simulation annealing and simulation technologies such as Flexsim in layout optimization, and focuses on the combined optimization method combining system layout design with intelligent algorithms and simulation technology. On this basis, the main challenges faced by data quality, multi-objective conflict, algorithm generalization, and computing cost are discussed, and future research directions such as digital twins, deep reinforcement learning, and multi-workshop collaboration are prospected. The results show that the closed-loop optimization framework integrating qualitative experience, quantitative optimization and dynamic verification can effectively reduce the material handling distance, improve the equipment utilization rate and the production line balance rate, and provide a reusable methodological reference for manufacturing enterprises to reduce costs and increase efficiency.

Keywords: Workshop Facility Layout; System Layout Design; Genetic Simulation Annealing Algorithm; Flexsim Simulation; Logistics Optimization; Manufacturing Workshop

1. Introduction

The global manufacturing industry is experiencing the fourth industrial revolution with "intelligent manufacturing" as the core. The implementation of national strategies such as Germany's Industry 4.0, the American Advanced Manufacturing Partnership Program, and Made in China 2025 marks that the manufacturing competition pattern has shifted from simple technology and scale competition to a comprehensive competition of efficiency, quality and flexibility. As the physical carrier and value creation core of the manufacturing system, the scientific nature of the workshop's facility layout directly determines logistics efficiency, equipment utilization rate and capacity potential. A large number of studies have shown that among the many factors affecting the overall efficiency of the production system, the impact of workshop layout on logistics costs can reach 30% to 50%, and the impact on the production cycle can reach more than 25%. Therefore, the optimization of workshop facility layout has always been the focus and difficulty of research in the field of industrial engineering.

In recent years, with the continuous development of domestic infrastructure investment, the rapid increase in the penetration rate of the new energy industry, and the widespread application of intelligent manufacturing technology, manufacturing segments such as construction machinery and heavy equipment have ushered in structural growth opportunities. However, industry competition has shifted from a single product performance competition to a full-value chain efficiency competition. According to industry research data, the workshop logistics cost of domestic heavy machinery manufacturing enterprises accounts for 15% to 22% of production costs, which is much higher than the level of 8% to 12% of the automobile manufacturing industry. One of the core reasons for this gap is that the workshop layout of many manufacturing enterprises still follows the extensive planning in the early stage of factory construction, lacking systematic and scientific optimization design and continuous improvement. With the increase in product types, the increase in customized demand and the intensification of order fluctuations, the disadvantages of the original layout are becoming increasingly prominent. The large spacing between the storage area and the assembly line leads to the long-distance handling of heavy parts, the coexistence of idle and congestion, the cross-redundancy of material handling paths, and the frequent drift of production line bottlenecks. These layout-related issues have become the core bottleneck restricting the efficiency improvement and cost control of manufacturing enterprises. At the same time, the Chinese government has clearly proposed to promote the transformation of the manufacturing industry to lean and intelligent, and encourage enterprises to improve production efficiency and reduce operating costs through technological transformation and process reengineering, which provides clear policy guidance and support for the upgrading of production systems of manufacturing enterprises.

Workshop layout optimization is closely related to the problem of production line balance. Production line balancing refers to the reasonable distribution of production tasks to each station under the premise of meeting the priority of operations, so that the operation time of each station is as equal as possible, thereby reducing waiting time and increasing output rate. Workshop layout optimization is to determine the location of each operating unit in space, which directly affects the material handling path and distance. A good layout can significantly shorten the material handling distance, reduce work-in-progress inventory, and balance the workstation load, thereby indirectly improving the production line balance rate. On the contrary, even if the process allocation achieves perfect balance in theory, unreasonable layout will lead to the intersection of logistics paths and the surge of handling time, making the theoretical balance impossible to achieve in practice. Therefore, collaborative optimization of facility layout, operation element allocation, and cycle setting is an inevitable requirement to maximize the overall efficiency of the manufacturing system.

However, compared with the assembly scenarios of electronics, light industry and other industries, the layout optimization of heavy machinery manufacturing workshops faces more complex constraints. First, the weight of parts is heavy. The weight of core components such as frames, hydraulic systems, and transmission boxes can reach several tons, and the transportation relies on special equipment such as trucks and heavy forklifts, and the cost and time of long-distance movement are extremely high. Second, the process coordination is complex. There are strict sequence and space adjacency requirements between welding, painting, final assembly, debugging and other processes, and some processes also require special environmental protection and safety conditions. Third, the equipment occupies a large area. Large presses, welding robot workstations, assembly lines, etc. occupy a lot of space, which is prone to interference between facilities, and the physical cost of adjusting the layout is extremely high. These special constraints make it difficult to directly apply the layout methods transplanted from the electronics and light industry industries, and there is an urgent need to build an optimization framework that adapts to the characteristics of heavy machinery manufacturing.

Based on the above background, this paper focuses on the optimization of manufacturing workshop facility layout, systematically sorts out the relevant theories and methods, analyzes the limitations of traditional methods, reviews the latest application progress of intelligent algorithms and simulation technology, and proposes a closed-loop optimization framework combining qualitative analysis, quantitative optimization and dynamic verification. Finally, this paper discusses the main challenges and future research directions, in order to provide theoretical reference and methodological guidance for manufacturing enterprises to realize the scientific optimization of workshop layout.

2. Overview of Workshop Layout Optimization Problems

2.1 Definition and Classification of Workshop Layout Optimization Problems

The workshop layout problem refers to the determination of the optimal position of each operation unit in a given plane space under the premise of meeting specific constraints, so as to optimize logistics cost, space utilization and production fluency. The operation units that need to be determined include various functional areas such as equipment, workstations, storage areas, inspection areas, and channels. This problem is essentially a combination optimization problem, and its solution complexity increases exponentially with the increase of the number of operation units, which is a typical NP difficult problem.

According to the dynamics of the time dimension, facility layout problems are mainly divided into two categories. The first type is static facility layout problems, which assume that the material handling volume and product process route remain unchanged during the planning cycle, and seek a fixed layout scheme that does not change with time. Static layout is suitable for production scenarios with stable product types and small output fluctuations. The second type is dynamic facility layout problems, which consider the phased changes in product structure, output or production process over time, allowing the layout plan to be replanned at different stages. Although dynamic layout can better adapt to market changes, its implementation cost is high, and it is usually suitable for industries with short product life cycles or frequent process updates.

In the actual production environment, heavy machinery assembly workshops are essentially quasi-static problems due to relatively stable product models but large output fluctuations and long order delivery cycles. However, with the increasing trend of personalized market demand, the dynamic adjustment of production plans is becoming more and more frequent, and it is difficult to meet the actual demand for completely static layout design. Therefore, the introduction of dynamic simulation technology to verify the robustness of the layout scheme to production fluctuations has become the consensus of current layout optimization research.

In addition, according to different layout forms, workshop layouts can also be subdivided into linear layouts, U-shaped layouts, unit layouts, hybrid layouts and other types. Each layout form has different logistics characteristics and applicable scenarios. The linear layout has a simple structure and is easy to manage, but there is more material return. The U-shaped layout is convenient for inter-workstation collaboration and is suitable for multi-variety mixed flow production. The unit layout organizes production units according to the product family, which can significantly shorten the material handling distance. Modern manufacturing workshops often adopt a hybrid layout strategy to balance efficiency and flexibility.

2.2 Special Constraints and Optimization Goals of Heavy Machinery Assembly Workshops

Compared with assembly workshops in electronics, light industry and other industries, heavy machinery assembly workshops face a series of unique constraints in layout optimization, which directly affect the establishment of optimization models and the selection of solution strategies.

First, the weight of parts and components. The core components of heavy machinery, such as frames, hydraulic pumps, transmission boxes, and engines, are extremely heavy, and a single piece can reach hundreds of kilograms or even several tons. The handling of these parts must rely on trucks, heavy forklifts or self-guided heavy-duty trucks, and the slow operation speed of the handling equipment, long acceleration and braking time, high energy consumption, and frequent long-distance handling will significantly increase logistics costs and prolong the production cycle. Therefore, the handling distance of heavy parts must be prioritized in layout optimization, while also considering the ability constraints of handling equipment and safe working space.

Second, the process is complex. The manufacturing of heavy machinery usually involves multiple process links such as welding, machining, painting, final assembly, and debugging, and there are strict sequence and space adjacency requirements between each link. For example, the welded workpiece needs to enter the painting process within the specified time to prevent rust, and the final assembly process needs to be adjacent to the debugging station for quick feedback of problems. These non-logistical relationships, that is, the closeness between operating units, have an important impact in layout design and cannot be characterized only by minimizing logistics costs.

Third, the equipment occupies a large area. Equipment such as large presses, welding robot workstations, assembly lines, and debugging benches occupy a large amount of workshop area, and sufficient safety spacing, operating space, and access must be reserved between equipment. In addition, the coverage of driving tracks and the load-bearing capacity of heavy material stacking areas are also physical constraints that cannot be ignored. These constraints lead to strict restrictions on the arrangement of locations between facilities, increasing the complexity of layout optimization.

Based on the above constraints, the layout optimization goal of heavy machinery assembly workshops needs to be expanded from a single minimization of total logistics cost to a multi-objective system. Specifically, logistics cost minimization is the core indicator, that is, the product of the weighted material handling distance and unit handling cost is minimized. Maximizing non-logistics relationships requires the closeness between each operating unit to be as high as possible, which can be quantified by assigning closeness levels. Maximizing area utilization requires improving the utilization efficiency of the internal area of the workshop and reducing idle and waste under the premise of meeting the requirements of safe spacing and operating space. Improving the production line balance rate reduces the downtime caused by material waiting and handling delays through reasonable layout, so that the working time of each station is as close to the cycle as possible. For example, placing closely related workstations close to each other shortens the handling distance, but may reduce the regularity of the workshop space, so it needs to be trade-off in the multi-objective optimization framework.

2.3 Traditional Layout Methods and Their Limitations

Before the popularization of intelligent algorithms, workshop layout design mainly relied on two approaches: one was a qualitative method based on experience and intuition, and the other was a semi-quantitative method based on system layout design.

The system layout design method was proposed by Muther in 1961 and is the most representative layout planning methodology in the field of industrial engineering. The core idea of this method is to draw location-related maps and area-related maps through systematic logistics analysis and interrelationship analysis of operating units, generate several candidate layout schemes based on comprehensive consideration of various constraints, and then select the optimal or optimal scheme through the weighted scoring method. The specific implementation steps include original data analysis, logistics analysis, interrelationship analysis of operating units, comprehensive interrelationship calculation, location correlation map drawing, area adjustment and correction, scheme evaluation and selection, etc

The system layout design method combines qualitative analysis with quantitative calculation, with clear logic and strong organization, and has achieved remarkable results in applications in electronic assembly, auto parts, food processing and other industries, which can reduce logistics costs by 10% to 30%. However, this method has obvious limitations in the application of heavy machinery manufacturing workshops.

First, static assumptions are separated from dynamic production. The system layout design is analyzed based on the average flow rate and fixed process route, which cannot reflect the dynamic disturbances such as bottleneck drift, order fluctuations, equipment failures, and material supply delays in actual production. In heavy machinery manufacturing, the actual flow of goods is often far from stable due to the large number of parts, long processing time, and large variables in production planning. The layout scheme based on static data design often has the problem of seemingly reasonable and congested in actual operation.

Second, the multi-constraint processing capacity is insufficient. In the face of multiple complex constraints such as heavy equipment occupancy constraints, driving coverage restrictions, safe passage requirements, and load-bearing area restrictions, it is difficult to accurately solve the global optimal or approximate optimal layout in the qualitative analysis of system layout design. Especially when the number of operating units is large, the workload of manually drawing position-related maps is huge, and it is difficult to ensure the quality of the scheme.

Third, there is a lack of closed-loop verification mechanism. The scheme generated by the system layout design is usually directly put into implementation, and there is a lack of high-fidelity dynamic simulation verification. This often exposes problems that cannot be foreseen in the planning stage after the implementation of the scheme, such as the serious accumulation of materials at a station, the logistics congestion of a certain channel, and the low utilization rate of a certain equipment, and the cost of physical adjustment is already extremely high. Therefore, using the system layout design method as a preliminary screening tool, combined with the quantitative optimization of intelligent algorithms and the dynamic verification of simulation technology, has become the mainstream direction to break through the limitations of traditional methods.

3. Application Status of Intelligent Algorithm and Simulation Technology in Workshop Layout Optimization

3.1 Application of Intelligent Optimization Algorithm

As the problem of workshop layout becomes more and more complex, scholars have begun to use intelligent algorithms or combine SLP with intelligent algorithms to find optimal or approximate optimal schemes for workshop layout. Gholizadeh proposed an efficient hybrid algorithm for truss structure layout, which combines cellular automata and particle swarm optimization, and the numerical results show that this hybrid algorithm can not only converge to a better solution, but also provide a faster convergence [1]. Samanta et al. set up a dual objective function when studying the facility layout of semi-automatic bus body manufacturing units, proposed an improved artificial bee colony algorithm, and combined it with genetic algorithm and neighborhood search algorithm to solve it, which performed better than other algorithms [2]. Guan et al. used a multi-objective particle swarm optimization algorithm combined with a two-stage method to solve the multi-objective function, and proved that this method can effectively solve the multi-objective workshop layout problem [3]. Liu and Zhao took the multi-line workshop layout as the research object, used the multi-objective fruit fly optimization algorithm to solve the model, and designed an olfactory search based on mixed step size to enhance the global search ability and stability [4]. Lewicki et al. used FlexSim simulation to optimize production processes, effectively eliminating bottlenecks and improving manpower utilization [5]. Yao et al. combined SLP with improved genetic algorithms to optimize workshop layout, effectively reducing logistics costs and improving the efficiency of operation unit collaboration [6].

3.2 Application of Simulation Technology

Since the 80s of the 20th century, computer applications have gradually become popular, and various simulation technologies have developed rapidly, becoming design tools with strong visibility in layout design. At present, the simulation software commonly used by designers mainly includes Witness, Matlab, Arena, and Flexsim. Prajapat et al. proposed discrete event simulation using Witness software to help decision-makers evaluate various layouts and configurations of factories [7]. Li et al. simulated and tested three assembly line layouts on the Witness software platform, and selected the optimal layout mode by comparing manufacturing costs, cycle balance, and production efficiency [8]. Said et al. used Arena simulation software to evaluate the existing production line layout and new improved layout of a bicarbonated beverage production company, and provided a more productive solution [9]. Zhou et al. applied Em-plant software in the layout design of a transmission workshop production line and optimized the workshop layout by comparing and analyzing the simulation results [10]. Zhu et al. used Flexsim software to model and simulate the operation process of a fruit and vegetable cold chain logistics distribution center, identified bottlenecks and idle resources, and optimized the operation process [11]. Xiong et al. used a new genetic algorithm to obtain a variety of feasible solutions when solving the dynamic layout problem, and used Flexsim software to simulate and obtain the best layout scheme [12]. Dou et al. used improved genetic algorithms to solve the facility layout model, which effectively shortened the order completion time and improved operational efficiency [13]. Lv and Feng proposed to improve the hunter-prey algorithm to solve the workshop layout problem, which improved the convergence speed and solution accuracy [14].

3.3 Research Progress of Combinatorial Optimization Methods

When studying the optimization of workshop layout, in addition to the most critical indicator of minimal logistics cost, there are other optimization goals that cannot be ignored. Suhardini et al. also took into account the constraint of maximizing the closeness of different operating units when solving the problem of workshop layout [15]. Zhang et al.

focused on the factor of area utilization and absorbed the two concepts of workshop area occupancy and space area utilization [16]. Jia et al. combined with the whole-body rapid assessment method to create a workshop layout optimization model including human factors, which reduced logistics costs and workers' cumulative fatigue index [17]. Zhang and Sun comprehensively considered the order of loading and unloading ports and facilities, constructed a mathematical model of the collection outlet, and verified the effectiveness of the model [18]. Zhu et al. constructed a multi-factor layout model with the goal of minimizing completion time and material handling [19]. Peng et al. constructed a mathematical model of a ship pipe processing workshop, and the optimal layout reduced logistics cost [20]. Bi constructed an intelligent manufacturing assembly line layout optimization model with the lowest logistics cost and the shortest AGV path [21]. Lu et al. constructed a workshop layout optimization model with the lowest logistics cost and shortest handling time, and took into account different material handling methods, and the results showed that the cost and time were reduced [22].

4. Challenges and Prospects

4.1 Current Main Challenges

Although the application of intelligent algorithms and simulation technology in workshop layout optimization has made significant progress, it still faces a series of practical challenges in the process of practical promotion to the manufacturing industry.

1. Challenges of data quality and real-time: The input data relied on for workshop layout optimization often has significant fluctuations and uncertainties in the actual manufacturing environment. Many manufacturing enterprises, especially small and medium-sized enterprises, have not yet achieved full-process IoT coverage, and some key data still relies on manual recording, which has problems such as measurement errors and missing records. If the optimization algorithm and simulation model run based on inaccurate data, the effect of the generated layout plan will be greatly reduced when actually implemented. Therefore, how to build an effective layout optimization model under limited and noisy data conditions is a fundamental problem that needs to be solved urgently.

2. Challenges of Multi-objective Conflict and Weight Calibration: Workshop layout optimization often includes multiple conflicting objectives. When integrating these objectives into a single-objective function, it is necessary to assign a weight coefficient to each sub-objective. There is a lack of unified scientific standards for the calibration of weight coefficients. The analytic hierarchy process relies on the subjective judgment of experts, the entropy weight method requires a large amount of sample data, and the Pareto solution set generated by the multi-objective evolution algorithm still requires the intervention of decision-makers. How to design an interpretable and easily interactive multi-objective decision-making mechanism is a current research difficulty.

3. Challenges of algorithm parameter sensitivity and generalization ability; The performance of algorithms such as genetic simulation annealing is highly dependent on the selection of parameters such as population size, crossover probability, variation probability, and annealing temperature. The optimal parameter combination calibrated for a specific workshop may not be directly transferred to other workshops. Improper parameter setting may lead to precocious convergence or waste of computing resources. Developing a parameter adaptive adjustment mechanism or designing a robust algorithm that is not sensitive to parameters is of great value for promoting the popularization of intelligent optimization methods.

4. Challenges of simulation model confidence and computational cost; In order to accurately simulate the complex dynamic behavior in heavy material handling, it is necessary to build a high-resolution simulation model, but this will lead to a long run time in a single simulation. If high-fidelity simulation is directly embedded in the fitness evaluation process of genetic algorithms, the computational overhead will be unbearable. How to strike a reasonable balance between fidelity and computational efficiency is a hot issue in the field of engineering simulation and optimization integration.

4.2 Future Research Directions

In response to the above challenges and combined with the development trend of intelligent manufacturing technology, in-depth research can be carried out in the following directions in the future.

1. Dynamic layout optimization driven by digital twins: The digital twin technology synchronizes real-time data from the physical workshop to the virtual model through the IoT platform, transforming layout optimization from offline static design to online dynamic adjustment. When bottleneck drift or order mutation is detected, the system can automatically trigger incremental layout replanning to re-optimize only the affected local areas. This requires the optimization algorithm to have fast response capabilities and adopt reinforcement learning strategies of offline training and online adjustment. The high-fidelity real-time simulation data of the digital twin can also be used to continuously calibrate the parameters of the optimized model to achieve true virtual control of reality.
2. End-to-end layout strategy of deep reinforcement learning: The traditional optimization and simulation separation mode requires artificial definition of objective functions, constraints, etc., which rely on a large amount of domain knowledge. Deep reinforcement learning provides a new end-to-end path, that is, modeling the workshop layout problem as a Markov decision process, and using algorithms such as deep Q network or near-end policy optimization to train the strategy network to directly output layout adjustment instructions. This method can independently learn the implicit optimization law without manually defining the objective function, and the trained model can be migrated to different scale workshops.
3. Multi-workshop collaboration and supply chain integration layout: Most current studies limit the scope of layout optimization to a single workshop, ignoring the material flow across workshops. Future research can extend layout optimization to the joint optimization of multiple workshops, warehouses, and even outsourcing manufacturers, build a factory-level material flow network model, and use distributed genetic algorithms to solve the global optimal facility landing point to further reduce the total cost of the supply chain.
4. Explainable layout decisions for human-machine collaboration: The layout schemes output by current intelligent algorithms are often regarded as black box results, and managers are reluctant to adopt them because they do not understand the optimization logic. Future research can embed interpretable modules in the algorithm to output reports that meet key constraints, comparative advantage charts, and the improvement contribution of each goal. Through the visual interactive interface, human experts can easily modify or reject algorithm suggestions, forming a human-machine mutual trust and collaborative decision-making mechanism.
5. Collaborative optimization of energy flow and logistics for green manufacturing: With the advancement of the dual carbon goal, energy flow analysis can be introduced into the future workshop layout optimization, including the energy consumption of material handling equipment and equipment standby energy consumption, and the construction of an integrated model covering material flow and energy flow, providing a new technical path for the green, low-carbon and efficient development of the manufacturing industry.

5. Conclusion

This paper focuses on the optimization of workshop layout in the manufacturing industry, systematically expounds the definition, classification, constraints and objectives of workshop layout problems, analyzes the limitations of traditional system layout design methods, reviews the application status of intelligent algorithms and simulation technology, and focuses on the combination optimization paradigm of connecting the three. On this basis, this paper summarizes the current practical challenges such as data quality, multi-objective conflict, algorithm generalization, and simulation computing cost, and looks forward to future research directions such as digital twin drive, deep reinforcement learning, multi-workshop collaboration, and human-machine collaborative explainable decision-making.

The following main conclusions are drawn. First, the traditional system layout design method has insufficient adaptability in dealing with the complex constraints of heavy machinery workshops, while the intelligent algorithm that relies solely on mathematical models lacks the ability to respond to dynamic disturbances. The closed-loop framework that integrates qualitative analysis, global optimization and dynamic verification is an effective way to improve the scientificity and feasibility of layout optimization schemes. Second, the genetic simulation annealing hybrid algorithm shows

better global convergence and solution quality than the standard genetic algorithm, which can effectively balance exploration and development. Third, simulation tools such as Flexsim can identify dynamic bottlenecks not considered by mathematical models before the solution is implemented, and significantly improve the production line balance rate and system robustness through iterative adjustment. Fourth, manufacturing enterprises can adopt the lightweight path of data collection, algorithm optimization, and local simulation to promote layout optimization in stages without one-time investment.
This paper provides a set of replicable workshop layout optimization methodological references for manufacturing enterprises. In the future, with the continuous maturity of digital twins, Internet of Things, and artificial intelligence technologies, workshop layout optimization will evolve from static and offline design activities to dynamic and online adaptive control systems, continuously releasing the efficiency potential of manufacturing systems, and providing strong support for the high-quality development of China's manufacturing industry.

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