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Workshop Layout Optimization Based on Improved SLP Method and Intelligent Algorithms: Literature Review and Innovative Directions

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ABSTRACT

In recent years, research on production workshop layout optimization has advanced rapidly in the context of intelligent manufacturing, with the integration of traditional Systematic Layout Planning (SLP) and intelligent algorithms emerging as a mainstream trend. This paper reviews the latest developments in workshop layout optimization, including: (1) The fusion of SLP and intelligent algorithms (e.g., genetic algorithms, sparrow search algorithm, particle swarm optimization), significantly improving logistics efficiency and non-logistics relationships; (2) The application of digital twins and immersive technologies (VR/AI), enabling dynamic adaptive adjustments and human-machine interaction validation; (3) The gradual incorporation of safety and sustainability factors into layout optimization. However, existing research still faces limitations such as insufficient dynamic adaptability, inadequate consideration of human factors, and lack of green metrics. To address these gaps, this paper proposes an "Intelligent-Human-Green" (IHG) collaborative optimization framework, combining dynamic multi-objective intelligent algorithms (e.g., a hybrid sparrow search-NSGA-III algorithm), VR-based human-factor safety assessment, and lifecycle carbon emission quantification. This framework aims to advance workshop layouts toward autonomous decision-making, dynamic adaptation, and sustainability. It holds significant potential for applications in discrete manufacturing, food and pharmaceutical industries, and high-risk workshops, with expected improvements of 25% in logistics efficiency, over 10% reduction in carbon emissions, and enhanced safety responsiveness.

KEYWORDS

Workshop layout optimization; Systematic Layout Planning (SLP); Intelligent algorithms; Digital twin; Human factors engineering; Sustainable manufacturing; Dynamic multi-objective optimization; Virtual reality (VR)

1. INTRODUCTION

With the rapid development of manufacturing and continuous improvements in production efficiency, the optimization of production workshop layouts has garnered increasing attention. A rational layout can enhance production efficiency, reduce costs, and strengthen market competitiveness. However, as research progresses and methodologies evolve, traditional SLP methods and single algorithms no longer suffice. This paper reviews recent studies on workshop layout optimization based on improved SLP methods and intelligent algorithms and proposes innovative research directions.

2. LITERATURE REVIEW

Recent research on workshop layout optimization has achieved notable progress in methodological innovation and technological integration. Key directions include:

2.1. Integration of Traditional Layout Methods and Intelligent Algorithms

Hu Jiaqi (2024) quantified non-logistics factors using the Analytic Hierarchy Process (AHP) to optimize clutch workshop layouts [1]. In newer studies, Bi Shenghao et al. (2024) proposed a layout optimization method based on the Sparrow Search Algorithm (SSA), reducing total transport distance by 26 meters and improving non-logistics relationships by 24.84% compared to traditional genetic algorithms [2]. Xu Xiaoming et al. (2020) combined SLP with particle swarm optimization [3], while Zhang Qinglei et al. (2020) developed a DMPSO algorithm for multi-objective problems [4]. Internationally, D Suhardini et al. (2019) integrated ALDEP (Automated Layout Design Program) with the CRAFT algorithm, demonstrating a 23% reduction in material handling costs [5].

2.2. Applications of Digital Twins and Immersive Technologies

Guo Hong fei et al. (2021) proposed a digital twin-based framework for discrete workshop layout optimization, enabling adaptive adjustments through real-time physical data feedback [6]. Liu Xiaopeng et al. (2024) developed a multi-layer cellular flow layout decomposition-coordination mechanism for small-batch customized production [7]. Zoi Arkouli et al. (2024) combined AI and immersive VR to generate layout solutions via genetic algorithms, allowing operators to evaluate reachability and posture comfort in VR, thereby reducing prototyping costs [8]. Li Shiqiang et al. (2021) further validated the efficiency of virtual verification in digital factory simulations [9].

2.3. Safety and Sustainability Considerations

A. Azadeh et al. (2013) introduced safety indices into maintenance workshop layouts, combining simulation and Data Envelopment Analysis (DEA) to balance efficiency and operational safety [10]. While most research prioritizes cost efficiency, Yang Jun et al. (2021) emphasized the need to optimize equipment connectivity and energy consumption in digital workshops [11]. Internationally, M. Rajesh (2016) used the CORELAP algorithm to optimize oven workshop layouts, indirectly reducing energy consumption, though carbon emission quantification remains underexplored [12].

2.4. Industry-Specific Customization and Complex Scenarios

Zheng Guanghui et al. (2023) proposed a genetic-harmony algorithm for high-speed train component workshops, balancing vibration prevention and space utilization [13]. Wei Zifang (2023) incorporated hygiene zoning constraints in food workshop layouts [14]. Ge Xiaomei et al. (2021) improved genetic algorithms to achieve Pareto optimality in equipment utilization, energy consumption, and safety, though most studies rely on static assumptions and lack dynamic adaptability [15].

3. RESEARCH GAPS

Current research has three main limitations: (1) Insufficient dynamic adaptability—most algorithms rely on static data and struggle with production plan changes or equipment failures; (2) Inadequate human factors engineering—few studies evaluate operator comfort; (3) Lack of sustainability metrics—green objectives like carbon emissions and resource recycling rates are not systematically integrated.

4. INNOVATIVE RESEARCH DIRECTIONS

This paper proposes an "Intelligent-Human-Green" (IHG) collaborative optimization framework, with core directions including:

1) Dynamic Multi-Objective Intelligent Algorithms: Develop a hybrid sparrow search-NSGA-III algorithm with Lévy flight mechanisms for high-dimensional convergence, integrated with digital twins for real-time data collection and dynamic objective functions.

2) Human-Machine Interaction and Safety Enhancement: Combine VR motion capture and AI generative design to quantify operator fatigue and establish layout-human factor safety models. Introduce a Safety Accessibility Index (SAI) to assess emergency evacuation efficiency.

3) Green Layout Evaluation System: Construct a lifecycle assessment (LCA) model to quantify energy consumption and carbon footprints. Incorporate a "carbon emissions per unit output" metric into multi-objective functions.

5. EXPECTED APPLICATIONS AND VALUE

Key application scenarios include: Discrete manufacturing (e.g., high-speed train component workshops): Dynamic equipment spacing adjustments for order fluctuations, expected to improve logistics efficiency by 25% and reduce carbon emissions by 10%. Food and pharmaceutical industries: Hygiene zoning optimization and digital twin monitoring to reduce cross-contamination risks and lower energy consumption by 15%. High-risk workshops (e.g., chemical maintenance): SAI-optimized layouts to shorten emergency response times by 30%

6. CONCLUSION

Intelligent manufacturing has driven rapid development in production workshop layout optimization research, where the integration of traditional Systematic Layout Planning (SLP) with intelligent algorithms has become a mainstream trend. Studies show that combining SLP with genetic algorithms, Sparrow Search Algorithm (SSA), Particle Swarm Optimization (PSO), and other intelligent algorithms significantly improves logistics efficiency and non-logistics relationships. Additionally, the application of digital twin and immersive technologies (VR/AI) enables dynamic adaptive adjustments and human-machine interactive validation, while safety and sustainability factors are increasingly being emphasized. However, current research still faces limitations, including insufficient dynamic adaptability, inadequate human factors engineering, and a lack of green metrics.

To address these challenges, this paper proposes an "Intelligent-Human-Green" (IHG) collaborative optimization framework, which incorporates dynamic multi-objective intelligent algorithms (e.g., hybrid SSA-NSGA-III), VR-based human factors safety assessment, and lifecycle carbon emission quantification to advance workshop layouts toward autonomous decision-making, dynamic adaptation, and sustainability. This framework demonstrates strong potential in discrete manufacturing, food & pharmaceutical industries, and high-risk workshops, with projected improvements of 25% in logistics efficiency, over 10% reduction in carbon emissions, and enhanced safety response capabilities. Future research should further explore dynamic optimization, human-machine collaboration, and green manufacturing to comprehensively enhance the intelligence and sustainability of production workshops.

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