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Review of Material Distribution Route Optimization

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Abstract: The optimization of material distribution routes is an important research field, aiming to enhance the efficiency and accuracy of material distribution by optimizing the distribution routes. This paper provides a review of the research on the optimization of material distribution routes. Firstly, it introduces the background and significance of the problem. Then, it describes the problem. Subsequently, it reviews and evaluates the research progress on different types of material distribution route optimization problems. Finally, it summarizes the current research status and existing challenges of the material distribution route optimization problem. Currently, certain achievements have been made in the practical application of the material distribution route optimization problem, but there are still some challenges, such as the efficiency and scalability of algorithms. Future research can further improve existing solutions, explore new algorithms and models to enhance the effectiveness of material distribution route optimization. In conclusion, the optimization of material distribution routes is a significant and challenging research field. By reviewing existing research results and problems, this paper provides references and guidance for further research on the optimization of material distribution routes.

Keywords: Material distribution, Path optimization, Multi-objective.

1. Introduction

Workshop material distribution connects all the links of production and manufacturing and is an important part of production logistics. An efficient material distribution system needs to deliver the materials required for production to the corresponding workstations in an appropriate way at the right time. The diversification of demands has intensified the complexity and uncertainty of the manufacturing workshop environment. Whether materials of various types can be delivered on time and in the right quantity will directly affect the smooth progress of production. Therefore, it is necessary to reasonably design the material distribution path and determine the distribution time. The optimization problem of workshop material distribution paths not only needs to meet the material demands of the production line but also needs to reasonably control production costs. With the development of technology, research on the optimization of material distribution paths of different types has made significant progress. Therefore, it is very necessary to thoroughly review the current research status of the material distribution path optimization problem and explore its future research directions. This will help to grasp the research focus and avoid repetitive and ineffective research.

2. Problem Description

Workshop material distribution route optimization problem is essentially a vehicle routing problem. The vehicle routing problem is a problem that aims to minimize the distribution cost under certain constraints. These constraints include but are not limited to: customer demand, customer demand time, vehicle capacity, etc. It is necessary to reasonably plan the order of delivery vehicles to visit customers in order to develop a vehicle distribution route scheme that maximizes the above objectives. However, logistics distribution route optimization is a complicated mathematical problem involving modern optimization algorithms, which is difficult to solve and requires a lot of calculation. In the early stage of the research, the attempts to solve this kind of problem mainly focused on the single objective optimization with the shortest driving path, the lowest consumption cost or the least time. However, with the development of technology, the research focus gradually turns to multi-objective optimization, which considers more diverse factors and is more in line with the actual process of workshop material distribution. At present, in the study of workshop material distribution in manufacturing enterprises, scholars mainly focus on two aspects of vehicle routing problem: model construction and solution algorithm. In the model construction, the main focus is the transition from single objective to multi-objective, from the aspects of optimization objectives and constraints, so as to improve the model, and use a variety of algorithms to solve, to achieve the synthesis of algorithms.

3. Research Status

3.1. Path Optimization Problem with Time Window

The Vehicle Routing Problem with Time Windows (VRPTW) is an important variant of the Vehicle Routing Problem (VRP), whose core goal is to design the lowest total cost distribution route while meeting the customer's specified service time window. This problem widely exists in logistics distribution, shared travel, emergency materials scheduling and other fields, and its complexity is reflected in: Dual constraint coupling: It is necessary to meet the vehicle capacity limit and time window limit at the same time, and the solution space is compressed by double constraints. Time window type difference: Hard Time Windows: The vehicle must arrive within the time window, otherwise the solution is not feasible (such as medical supplies delivery). Soft Time Windows: Allows overtime service but incurs penalty costs (e.g., express logistics). Dynamic challenges: In actual scenarios, customer needs and traffic conditions may change in real time, requiring dynamic adjustment of routes.

In this context, Molina et al. [1] proposed a hybrid ant colony algorithm with local search, and verified the good performance of the method through experiments. Bogue et al. [2] proposed a column generation algorithm and a post-optimization heuristic algorithm to solve the problem. Jalilvand et al [3] developed a two-stage stochastic model and proposed a recursive hedging algorithm for vehicle routing problems with two-stage time window allocation and random service time. Tilk et al. [4] designed a branch pricing cutting algorithm to solve the model. Hoogeboom et al. [5] adopted the branching-cutting method to solve the model with the goal of minimizing travel time and the risk of violating the time window.

In recent years, information technology has provided the basis for real-time production to drive material distribution. Ibrahmi A [6] adopted the intelligent perception network to obtain real-time production data of stations, and determined each delivery time window by the time point of material delivery and the speed of material consumption to improve the accuracy of material delivery. However, the fluctuation of material consumption speed caused by uncertain factors was not considered, and Fuping Zhu [7] proposed a method combining real-time production data with normal fuzzy numbers to calculate the time window. Establish a cost penalty function for vehicles that cannot arrive within a specified time window. Aiming at the lowest distribution cost, a model was established and an improved genetic algorithm was used to solve the optimization problem of workshop material distribution path.

3.2. Multi-Objective Path Optimization Problem

With the deepening of the research on route optimization, the single objective optimization framework has been unable to meet the multi-dimensional demands of modern logistics system for efficiency, sustainability and service quality. The traditional vehicle routing problem (VRP) focuses on cost or distance minimization, and its model assumptions often simplify the complexity of multiple factors interweaving in real-world scenarios - for example, shortening transport paths can increase carbon emissions, while reducing the number of vehicles in use can lead to individual vehicle overloads or delays. This kind of conflict between objectives has prompted the academic circle to turn the research perspective to Multi-Objective VRP (MO-VRP), which aims to provide decision-makers with Pareto optimal solution sets to weigh different interest demands by synergistically optimizing multiple competing objectives.

In recent years, the emergence of emerging scenarios such as intelligent manufacturing and green logistics has further highlighted the practical significance of multi-objective optimization. For example, in the new energy vehicle scheduling, it is necessary to optimize the charging cost, driving time and battery loss at the same time; In the distribution of emergency materials, the timeliness of delivery and resource coverage should be balanced. This kind of demand promotes the leap of multi-objective optimization method from theoretical model to engineering practice, and gives birth to the core research directions of algorithm design, preference modeling and dynamic adaptability. The following will systematically review the methodology evolution, key technical challenges and cutting-edge solutions of multi-objective path optimization to reveal how it breaks through the limitations of single-objective paradigm and provides theoretical support and practical tools for the global optimization of complex logistics systems. In this regard, Qixiang Li et al. [8] took into account that the fixed cost generated by the different number of customer points served by the vehicle also changes to a certain extent during the actual distribution process, and built a multi-objective mathematical optimization model aiming at the total cost of vehicle distribution and average customer satisfaction, and also considered the factors that the vehicle speed changes with road conditions during the distribution process. More realistic, Jin Xu et al. [9] aiming at the problems of low vehicle utilization rate, single model of distribution car and reverse logistics in the current flexible workshop, built a bidirectional material distribution model considering multi-vehicle collaborative distribution by minimizing the sum of vehicle delivery cost, route transportation cost and time penalty cost as optimization objectives.

In addition, with the increasingly serious problem of environmental pollution, green logistics has attracted great attention from the government and enterprises. In this context, the interest in utilizing electric vehicles for logistics operations has increased dramatically. However, electric vehicles typically have limited range, relatively long charging times, and must rely on limited fuel infrastructure, which presents important challenges. It has been suggested in the literature that the above issues can be addressed through more efficient planning of electric vehicle pathways [10]. Therefore, the study of electric vehicle routing problem (EVRP) has become a research hotspot. The existing literature on EVRP mainly focuses on the optimization of costs and energy consumption related to driving distance. Erdogan and Miller-Hooks [11] first proposed the Green Vehicle Routing Problem (GVRP). The use of Alternative Fuel-Powered Vehicles (AFVs) in transportation. Considering the limited driving range of the vehicle and the limited refueling infrastructure, the model is built with the goal of minimizing the driving distance. Therefore, the proposed method is directly related to the modeling transformation of electric vehicles. Subsequently, the most economical driving path of electric vehicles was studied from the perspective of energy consumption rather than driving distance [12]. On this basis, Goeke and Schneider [13] proposed the Electric Vehicle Routing problem with time window and hybrid fleet (EVRP-TWMF), which incorporated speed, slope and cargo load distribution into the energy consumption model. Xiaoyong Zhu et al [14]., aiming at the problems of high carbon emissions, low distribution efficiency and high cost in the process of material distribution in manufacturing workshops, established a multi-objective workshop material distribution path optimization model and adopted an improved genetic algorithm to solve the model. At present, there are two main ways to provide fuel for electric vehicles, namely direct charging and replacement (BS). BS method is widely used because of its advantages such as low cost and short operation time. Several studies have established planning models and analyzed battery management strategies as well as facility deployment in battery exchange stations (BSS). A comprehensive comparison of the above literature shows that EVRP research largely focuses on single-objective optimization. In addition, the literature often ignores the influence of the power replenishment process. However, in studies that consider the power replenishment process, they only focus on the impact of route choice on construction and routing costs, and the time window is usually ignored. In order to make up for these deficiencies, Binghai Zhou et al. [15] tried to study the comprehensive impact of power replenishment process and time window on route planning of electric vehicles, and tried to optimize the total distribution cost and the average utilization rate of batteries at the same time. But they did not consider the load of the electric vehicle and the effect of the acceleration or deceleration process on electricity consumption. In addition, the carrying capacity of different types of materials should also be different. In the future research, we can also improve the problem scenario to make it more in line with the actual production.

3.3. Dynamic Path Optimization Problem

In the workshop logistics system, the essence of dynamic path planning can be seen as the continuous decision-making process of multi-objective optimization in space-time dimension. This process not only needs to deal with the traditional static trade-offs (such as cost, time, and energy consumption) between multiple objectives, but also needs to deal with the dynamic constraint reconstruction and target weight shift caused by real-time changes in the environment. In the automotive welding workshop, for example, when a welding robot is suspended due to a fault, the AGV needs to re-plan its path to go around the fault area in a few seconds, while ensuring that the material supply to other stations is not interrupted - which requires the optimization algorithm in a very short time window. Re-evaluate the priorities of path safety (avoiding secondary congestion), timeliness (minimizing task delays), and resource efficiency (AGV idle rate), and generate new Pareto efficient solutions. The complexity of such scenarios stems from dynamic coupling at three levels: Task dynamics: Sudden task insertion: The AGV task queue needs to be adjusted in real time for additional material needs caused by urgent orders or quality rework. Task priority shift: Stations at different production stages may dynamically adjust the urgency of material requirements (for example, the flow of a batch of workpieces needs to be accelerated due to temperature and humidity changes in the spray shop). Environmental dynamics: Physical space usage: Events such as temporary storage and device maintenance occupy channels cause the path network topology to change in real time. Human-machine interaction uncertainty: In the hybrid scene of artificial forklift truck and AGV, the randomness of human movement trajectory increases the difficulty of collision risk prediction. Resource dynamics: Abnormal vehicle status: AGV power shortage, mechanical failure or speed degradation, need to dynamically adjust the fleet scheduling strategy. Facility collaboration constraints: When transferring materials across workshops, differences in communication protocols and navigation rules of AGVs in different regions may lead to synergy failures. To address these challenges, current research is advancing along two main lines: Dynamic multi-objective modeling technique: the parameters such as time window and resource state are extended from fixed values to time series functions or random processes. For example, Markov decision process (MDP) is used to describe the randomness of task arrival, or fuzzy logic is used to describe the uncertainty of human-computer interaction.

With the development and application of emerging technologies in Industry 4.0, enterprises are increasingly deploying smart devices to enhance the flexibility of their manufacturing processes to meet the individual needs of their customers. In this case, they are introducing flexible devices such as automated guided vehicles for material handling in the workshop [16]. Automatic Guided Vehicles (AGVs) are mostly used in industrial systems, such as warehouses, manufacturing, container terminals, etc. In recent years, the research related to AGV dispatching has received extensive attention. The AGVs scheduling problem (AGVSP) can be divided into two related sub-problems: a scheduling problem and a routing problem. Thus, AGVDP can be thought of as a variant of the Vehicle Routing Problem (VRP). While there is extensive literature on AGVDP, this literature does not consider perturbation and dynamic cases. In practical applications, however, there may be significant variations in the factors that determine AGV scheduling, such as the accuracy of the scheduling plan created by the upper level planning system and the unloading efficiency. Lei Liu et al. [17] proposed a mixed integer optimization model with soft constraints on material order delivery satisfaction and two objectives: transportation cost and delivery time deviation for the uncertainty of workstation replenishment time and randomness of AGV unloading efficiency. Moreover, a comprehensive numerical experiment is carried out based on a numerical example constructed in a real scenario to verify the effectiveness of the proposed model and algorithm. In addition, because of the different characteristics of AGV, it should also be considered in the path planning. Cao Yu et al. [18] explored the particularity of AGV bidirectional transportation in the AGV scheduling problem, and provided an operational optimization method and management insights for ACT from the operational level. They propose a model that considers equipment coordination, bidirectional conflict-free routing, and import/export container tasks, with the goal of minimizing the completion time of all tasks. To solve the model, a bidirectional differential evolution algorithm based on dynamic routing methods was developed.

4. Summary

Although the above research has made some progress, there are still some problems such as poor solution quality, easy to fall into local optimal and seldom consider environmental factors in logistics distribution path formulation. It can be found that domestic and foreign scholars on the discrete workshop workstation logistics distribution path optimization research have achieved some results. Scholars at home and abroad have studied the two issues of low-carbon logistics and workshop workstation logistics distribution path optimization respectively, but there are not many studies combining the two. As the national carbon emission governance becomes more and more standardized, the implementation of carbon tax policy is getting closer and closer, manufacturing enterprises must integrate the low-carbon concept into the internal logistics activities of vehicles in the operation process, in order to reduce the pressure brought by environmental costs. In addition, the existing literature generally only considers one or two constraints, and there are few studies on the model of multi-constraint multi-objective dynamic vehicle routing problem. Therefore, the multi-objective green material distribution path planning with mixed constraints should be emphasized in the follow-up research. In summary, the author believes that the material distribution scheduling problem of AGV trolley in workshop can be studied with the goal of minimizing production cost and carbon emission, and the scheduling of the machine can be included in the discussion scope. In the real workshop, material distribution and machine scheduling are two inseparable links, and it is more practical to conduct collaborative research on them, which can reduce the cost and improve the production efficiency overall. In addition, dynamic factors of AGV and machine should also be considered, such as AGV charge and discharge problems and machine failures, which are often occurring in actual production

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