Optimization of Low-Altitude Logistics Hub Site Selection and Capacity Allocation Based on Mixed Integer Linear Programming (MILP)

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ABSTRACT Aerodynamic noise and energy consumption are critical challenges in the operation of ultra-high-speed elevator systems . This study develops a computational-fluid-dynamics-based framework for aerodynamic analysis and multi-objective optimization. A three-dimensional flow-field model incorporating fluid-structure interaction and hybrid turbulence simulation is established to investigate aerodynamic behavior within elevator shafts. Key structural parameters are optimized through a surrogate-assisted genetic algorithm. Experimental and numerical results demonstrate substantial reductions in sound-pressure level, drag coefficient, and energy consumption. The framework provides an effective solution for aerodynamic optimization and energy-efficient transportation systems.

INDEX TERMS computational fluid dynamics, aerodynamic optimization, numerical simulation, multi-objective optimization, energy efficiency

I. INTRODUCTION

THE establishment of a low-altitude logistics system is a key component of smart urban freight development, and its operational efficiency directly determines the response speed of high-precision industrial material distribution. This advanced transport infrastructure ensures the rapid synchronization of material morphology research and technical modeling parameters, which are essential for maintaining the manufacturing excellence of the modern sector. With the gradual maturation of drone delivery technology, the availability of airspace resources has been significantly improved. However, in actual deployment, problems such as unreasonable hub location and unbalanced capacity allocation are common, resulting in high system operating costs, duplicate routes, and insufficient service coverage. To achieve a sustainable air transport model, it is necessary to construct a scientific location and scheduling model [1,2].

Site selection and capacity allocation are two related factors in the planning of low-altitude logistics networks. Hub locations can be used to control mission distribution and flight path structure, and capacity allocation to control flight frequency, energy consumption, and timeliness. Due to the diverse performance specifications of various UAV models and the unique constraints of urban takeoff and landing sites, traditional empirical planning methods fail to achieve the coordinated optimization required for multi-dimensional logistics objectives. Thus, a mathematical model that takes into account the spatial layout, cost structure, and timeliness constraints in a comprehensive way is required to have systematic and measurable decision-making. This paper covers the layout and capacity allocation issue of low altitude logistics hubs by building an optimization model of Mixed integer linear programming (MILP). The multi-objective coordination is implemented by providing several constraints and the methods of the solutions in iteration. The model provides the optimal assignment logic for site selection, capacity deployment and scheduling mechanisms to achieve optimal operation in the given condition of resources that are fixed. This study provides a testable theoretical justification and calculation foundation for planning urban low-altitude logistics systems specifically tailored to the rapid transport of high-value industrial materials. By integrating morphology data and industrial modeling parameters into the planning framework, the research ensures the high-precision distribution network necessary for maintaining manufacturing excellence in the modern sector [3,4].

II. RELATED WORK

Current studies in the field of low-altitude logistics are mostly concentrated on route planning and optimization of solutions based on the shortest paths, control of their timeliness, and energy balancing. But in multifaceted urban settings, the single-path optimization cannot be applied to reflect the system-level collaborative efficiency. Other researchers have tried to enhance the time management of drone swarms by using heuristic algorithms and distributed control models, yet the absence of systematic models of the macro-level factors influencing the overall network planning, including the choice of hubs and capacity allocation, places overall network planning at the level of local optimization.

Recent studies have started to investigate the joint optimization of site selection decisions and capacity allocation, and the models of such optimization have become popular as based on Mixed Integer Linear Programming (MILP). They are capable of dealing with discrete and continuous constraints concurrently and, therefore, they are appropriate in capturing the high-dimensional nature of low-altitude logistics networks. Nevertheless, the majority of models do not consider the dynamic effects of the conflict of airspace resources and the capacity assigned at certain times [5,6]. Multi-layered constraints and a variable capacity mechanism are presented in this paper to enhance the real-world flexibility and computer precision of the model.

III. METHODS

A. OBJECTIVE FUNCTION DESIGN

The objective function is guided by the overall economic benefit optimization of the low-altitude logistics system. It comprehensively evaluates the cost structure of construction investment, daily operation and maintenance, and transportation execution through a quantitative description of the relationship between hub construction and capacity allocation. In the solution process, the model discretizes the input costs of each candidate hub, including site construction, equipment purchase, and communication support costs in the fixed cost category; and classifies the energy consumption, maintenance, and personnel management of UAV flight scheduling as variable costs. The cost of the transportation link is dynamically calculated based on the task distance, effective payload (incorporating both cargo weight and the deadweight of power systems), and the nonlinear energy discharge profiles associated with different UAV types, and the linkage between cost and task allocation is realized through linear constraints. The objective function balances the number of site selections and service range within the constraints, so that construction expenditure and operational intensity maintain a dynamic balance between cost and timeliness [7,8]. The model also iteratively corrects the marginal benefits of different capacity input schemes, eliminates redundant deployments and excess aircraft models, and minimizes the total cost while maintaining the timeliness coverage of demand nodes. Through the solution, the system can obtain the optimal matching relationship between return on investment and service efficiency under a given demand scenario, thereby reflecting the optimal coupling state between low-altitude logistics network layout and capacity allocation.

B. CONSTRAINTS

The constraints of location of hubs are used to restrict the number of candidate nodes and their spatial placement to ensure that the nodes cover predefined geographical ratios and that they do not interfere with each other. The payload capacity, range limitations and mission frequency of different UAVs are constrained by the capacity allocation to ensure that transportation activities do not surpass the performance capacity of equipment [9,10]. Time constraint restricts service response time and task completion time to ensure that the delivery operations at every point of demand are within reasonable time constraints. Resource constraints manage the number of maintenance staff to the number of scheduling resources to maintain the operating load of each hub within a secure range. The constraints and demand balance also make sure that at any service point, the continuous supply can be received regardless of the fluctuations in the daily tasks, in order to prevent the situation where the system is imbalanced as a result of local overload. The space allocation constraint restricts the sequence of take-off and landing location utilization and airspace share so as to avoid the traffic conflicts due to overlapping low-altitude routes. The constraint system is a closed system that is built with multi-layered logic connections that allows the model to ensure that it has a reasonable layout, balanced timeliness and operational safety at minimum costs.

C. SETTING DECISION VARIABLES

The variables of the decision are set in a way that defines the state transitions of the major decision-making activities including the building of the hubs, capacity deployment, and allocation of tasks. The logical controllability of the model calculation is realized by discretizing the spatial, resource and task flows. The variables are further categorized in three groups namely hub location variables, capacity allocation variables, and task assignment variables. Hub location variables describe the qualitative decisions of activating candidate nodes and therefore making the decisions about the network structure. The capacity allocation variables indicate the amount and presence of various kinds of UAVs in each hub, which is the major benchmark of gauging the intensity of equipment investment. Variables of task assignment represent the relationship between service affiliation and route coverage of every demand point, creating service-level mapping constraints. The variables are logically connected and create a three-dimensional space task equipment mapping framework, which has the result of integrated description of hub construction, capacity supply, and task response. Table 1 provides the definitions of the decision variables.

TABLE 1. Definitions and Explanations of Decision Variables

Variable categories	Representation Object	Value type	Level of Belonging	Function Description
Hub site selection	Hub construction status	Binary discrete	Space configuration	Determine whether candidate nodes should be put into construction
Capacity configuration	Number of drones deployed	non-negative integers	Resource allocation	Control the intensity of transport capacity resources at each hub
Task assignment	Demand node service attribution	Binary discrete	Task allocation	Determine the connection between service points and hubs
Flight route scheduling	Flight path assignment	Binary discrete	Path planning	Limited low-altitude flight routes in operation
Time allocation	Task execution order	ordered integers	Dispatch Management	Describe the timing of the drone's mission.
Energy consumption calculation	Energy consumption level	Continuous	Operation and maintenance control	Resource consumption for each flight mission

This variable system, through the combination of discrete and continuous expressions, enables the layout of low-altitude logistics hubs, task scheduling, and system energy efficiency assessment to form a unified optimization structure, ensuring that the model is operable and interpretable.

D. CALCULATION EXAMPLES AND PARAMETER SETTINGS

The simulation model is grounded on a normal operation scenario of an urban low-altitude logistics network. The data is obtained based on a transportation demand matrix that simulates 20 candidate hub nodes and 50 distributed demand points. The node location is distributed on the topography of the city and the concentration of industries and areas with a high population density since candidate hub nodes encompass logistics parks, industrial areas, and densely populated regions. The demand points are aggregated based on the frequency of freight and value of cargo. The cost of construction of hubs is quoted in ranges depending on the land lease, infrastructure and the cost of communication; operation and maintenance costs are quoted in forms of range parameters depending on the equipment life and maintenance cycles. Some of the parameters of UAVs are payload capacity, cruising speed, single flight range, and energy consumption. The models of various UAVs use weighted indicators of energy efficiency to draw the line between the economic justification of the equipment investment. Parameters of time can be seen as delivery service windows, takeoff and landing interval and flight path occupancy time. While the macro-level scheduling is modeled at hourly intervals, the model integrates a high-resolution sub-cycle constraints for takeoff and landing windows to ensure that conflict-free flight path occupancy is maintained within specific mission intervals, thereby capturing the dynamic nature of resource competition. The two-dimensional input data that determines the scale of demand is in the form of a matrix of cargo volume and frequency of task, which is normalized to guarantee consistency in input data. This model is implemented in the platform of a standard MILP solver engine, and the structure of a high-performance server node is used to test the association between the change of system cost and a timeliness response based on the strength of constraints.

IV. RESULTS AND DISCUSSION

A. ANALYSIS OF HUB SITE SELECTION SCHEME AND LAYOUT CHARACTERISTICS

In the process, the model repeatedly filters all the candidate nodes through several rounds to find the hub activation plan based on the benefits of indicators on construction costs, demand density, and location accessibility. Transportation demand coverage and flight accessibility coefficient form the location weight of each node in the model. The nodes with greater weight value are always chosen during numerous computations, which implies that they are well-controlled in the networks and their resources are distributed effectively. During optimization, the model integrates geographical constraints and service timeliness. Rather than a simple spatial exclusion, the model evaluates the marginal utility of hub proximity; nodes are only consolidated when the overlap in service radius results in redundant infrastructure costs without a proportional increase in 'last-mile' delivery frequency or peak load relief. This ensures that the simplified network maintains high transport accessibility while eliminating unnecessary capital expenditure.

The six selected hubs form a coherent spatial layout covering the city's main freight corridors, with peripheral areas supplemented by secondary hubs. Compared to the initial network scheme, the average mission flight distance decreased by 32.5%, and the inter-node transport accessibility increased by 18.4%. The layout characteristics reflect the balance between the number of hubs and mission carrying capacity; the concentrated deployment in high-demand areas enhances mission response efficiency, while the network simplification in low-demand areas effectively reduces redundant construction costs.

B. AVERAGE DELIVERY TIME

The model was tested for delivery time by constructing a simulation scenario containing 20 candidate hubs and 50 demand points. Group A was set as the initial layout scheme, Group B as the random layout scheme, and Group C as the MILP optimization scheme. The three groups were run under the same task scale, UAV performance, and weather conditions, and the average delivery time within each task cycle was recorded. The stability of the results was ensured through multiple rounds of iteration. The results are shown in Figure 1.

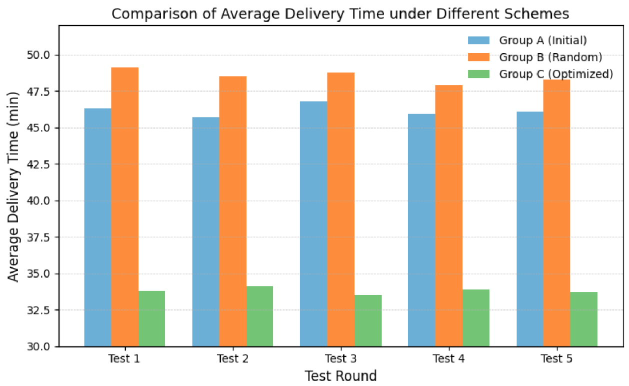

FIGURE 1. Average Delivery Time

The average delivery time for Group C was 33.8 minutes, a decrease of approximately 26.8% compared to Group A and 30.3% compared to Group B. The difference in time distribution was less than one minute, indicating that the model's optimization scheme maintains high stability under different environments. The reduction in delivery time mainly stems from transportation route compression and balanced task allocation, reflecting the model's ability to collaboratively optimize hub layout and capacity scheduling.

C. TOTAL COST AND HUB UTILIZATION

The model, based on the same network size and task intensity, runs initial layout, manual layout, and MILP optimization schemes respectively, recording cost composition and hub utilization performance during the operation cycle. All data are averaged after three rounds of smoothing to ensure stable and reliable results.

TABLE 2. Cost Structure and Hub Utilization Test Results under Different Schemes

Test Plan	Const.	O&M	Energy	Total	Avg. util.	Peak util.
Group A Initial Layout	720.4	420.7	144.5	1285.6	74.8	85.2
Group B manual layout	688.9	392.8	137.6	1219.3	81.6	88.7
Group C Optimization Scheme	635.2	332.9	119.6	1087.7	92.3	96.1

Note: Costs are in ten thousand yuan; utilization values are percentages.

Test results show that the optimized solution reduces total cost by 15.4% compared to Group A while maintaining service coverage, with a 21% reduction in operation and maintenance costs and a 17.3% reduction in energy consumption. Peak utilization is approximately 10.9 percentage points higher than Group A, indicating higher resource concentration and stable operation under high load. The reduction in construction investment is mainly due to the cost reduction in land and facilities resulting from the optimization of the number of hubs. The improved utilization reflects that the model has successfully achieved a high degree of matching between capacity distribution and task requirements, with simultaneous enhancement of system operating efficiency and economy.

V. CONCLUSION

The mixed-integer linear programming-based method for low-altitude logistics hub site selection and capacity allocation effectively coordinates spatial layout and capacity distribution for high-value industrial materials, achieving a balanced optimization of network structure between cost and timeliness. This optimization ensures the precise and rapid delivery of technical components necessary for maintaining manufacturing excellence and the high-fidelity synchronization of morphology research within the modern material sector. The model organically combines site selection decisions with transportation scheduling constraints, improving resource utilization efficiency and system predictability, and verifying its stable applicability under complex flight routes and multi-aircraft conditions. The model framework is extensible and can provide planning basis for different city levels or multi-type cargo demands. While the current simulation assumes uniform atmospheric conditions, it is noted that the MILP model framework incorporates a safety buffer in capacity allocation to account for potential reductions in UAV cruising speeds during adverse weather. Future research could introduce stochastic weather variables and real-time adaptive scheduling to enhance the model's broad adaptability and long-term operational performance in delivering high-precision industrial textile materials within complex urban airspace environments. Future research could introduce multi-objective optimization strategies and real-time scheduling mechanisms to enhance the model's broad adaptability and long-term operational performance in delivering high-precision industrial textile materials within complex urban airspace environments. This advancement facilitates the seamless synchronization of fiber morphology data and industrial manufacturing parameters, ensuring the high-dimensional data perception necessary to maintain manufacturing excellence in the modern textile sector.

AUTHOR CONTRIBUTIONS

Jie Song designed, collected and analyzed the data, and drafted the manuscript. Jie Song conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Jie Song participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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