

Article

# Layout Optimization of Logistics and Warehouse Land Based on a Multi-Objective Genetic Algorithm—Taking Wuhan City as an Example

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**Abstract:** With the rapid development of the logistics industry, the demand for logistics activities is increasing significantly. Concurrently, growing urbanization is causing the space for logistics and warehousing to become limited. Thus, more and more attention is being paid to the planning and construction of logistics facilities. However, due to spatiotemporal trajectory data (such as truck GPS data) being used less often in planning, the method of quantitative analysis for freight spatiotemporal activity is limited. Thus, the spatial layout of logistics and warehousing land does not match the current demand very well. In addition, it is necessary to consider the interactive relationship with the urban built environment in the process of optimizing layout, in order to comprehensively balance the spatial coupling with the functions of housing, transportation, industry, and so on. Therefore, the layout of logistics and warehouse land could be treated as a multi-objective optimization problem. This study aims to establish a model for logistics and warehouse land layout optimization to achieve a supply–demand matching. The proposed model comprehensively considers economic benefits, time benefits, cost benefits, environmental benefits, and other factors with freight GPS data, land-use data, transportation network data, and other multi-source data. A genetic algorithm is built to solve the model. Finally, this study takes the Wuhan urban development area as an example to practice the proposed method in three scenarios in order to verify its effectiveness. The results show that the optimization model solves the problem of mismatch between the supply and demand of logistics spaces to a certain extent, demonstrating the efficiency and scientificity of the optimization solutions. Based on the results of the three scenarios, it is proven that freight activities could effectively enhance the scientific validity of the optimization solution and the proposed model could optimize layouts under different scenario requirements. In summary, this study provides a practical and effective tool for logistics- and warehouse-land layout evaluation and optimization for urban planners and administrators.

**Keywords:** multi-objective optimization; land for logistics and warehousing; spatiotemporal data; genetic algorithm; NSGA-II; layout optimization



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## 1. Introduction

As the logistics industry experiences swift expansion, there is a marked increase occurring in the demand for logistics operations. Simultaneously, the process of urbanization is leading to a scarcity of space allocated for logistics and warehousing functions. Thus, modern cities are facing enormous logistics challenges, such as how to achieve the fast delivery of goods and adequate levels of inventory management, transportation efficiency, and traffic efficiency, as well as the surge in urban logistics demand placing enormous stress on cities [1]. However, in the development of modern urban logistics, the focus is not only on economic growth but also on environmental protection and urban operational

efficiency. Therefore, it is critical to strike a balance between logistics development and urban space utilization.

As an important service industry in a city, the logistics industry is closely related to various city functions, and the mutual influence and function are directly related to the formation of the urban layout structure. Urban logistics space is a type of space that seeks a balance between the development of the logistics industry and the multifunctional development of a city because it determines the allocation of urban logistics resources and has a significant impact on the urban built environment. At present, most studies on logistics space focus on logistics nodes and networks. For example, in the study of logistics nodes, it is found that the operational efficiency of logistics nodes can be improved by constructing an optimization model for optimizing the locations of logistics nodes [2–4]. In addition, in the study of logistics networks, the analysis of network structures is used mainly to construct a spatial model of logistics resource integration in order to optimize the allocation and operational efficiency of logistics resources [5,6]. However, there are relatively few studies on land for logistics and warehousing that reflect the allocation of spatial resources. Therefore, it is important to explore the relationship between urban logistics and refined urban development from the perspective of logistics and warehouse land use [7].

Most early studies on logistics and warehouse land use often construct a quantitative multivariate linear regression model to explore the relationships between changes in logistics and warehouse land area and each driving factor [8]. They comprehensively evaluate logistics and warehouse land use [9], and propose relevant suggestions for the management of logistics and warehouse land [10,11], which make a great contribution for urban planning. However, it is difficult to deal with non-linear relationships and spatial interactions between this land and other types of land [12]. The spatial layout optimization process for logistics and warehouse land involves comprehensive tradeoffs and considers multiple conflicting and interacting objectives. For example, from the perspective of environmental benefits, urban planning decision-makers should not only consider the direct economic benefits brought about by the optimization of urban logistics warehousing land use but also balance the impact of such optimization on the urban built environment brought about by the growth of economic benefits [13–18]. The complexity of land-use optimization for logistics and warehouse land is reflected not only in the balance of multi-objective optimization but also in the computational complexity of large-scale urban logistics and warehouse spatial units. A large-scale multi-objective land-use optimization scenario for logistics and warehouse land always requires a complex optimization process, which aims to arrive at a credibility planning scheme with a great deal of spatial calculation. Therefore, it is particularly important that appropriate methods are chosen to solve complex optimization problems that linear regression models could not satisfy.

To address the high-level computational complexity of spatial units in the multi-objective optimization process, most researchers have focused on the potential of heuristic algorithms in land-use optimization [12,19], such as the simulated annealing algorithm, ant-colony optimization algorithms, particle swarm optimization, artificial bee-colony algorithms, and so on [20,21]. The simulated annealing (SA) algorithm is a probabilistic technique used for finding an approximate solution to an optimization problem. It is inspired by the annealing process in metallurgy, where a material is heated and then slowly cooled to decrease its internal energy and reach a minimum energy state. In the context of land-use layout optimization, the SA algorithm is useful for solving complex problems that involve arranging various land-use types to optimize certain objectives, such as land value, accessibility, environmental impact, or a combination of these factors [22–24]. The ant colony optimization (ACO) algorithm is a metaheuristic algorithm that is inspired by the foraging behavior of ants. The ACO algorithm uses a similar concept to solve optimization problems, including those related to land-use layout optimization. For land-use layout optimization, the problem typically involves determining the best allocation of different types of land use (such as residential, commercial, industrial, and green spaces)

within a given area to optimize various objectives. These objectives can include factors like economic efficiency, environmental sustainability, social equity, and infrastructure development [25–28]. Particle swarm optimization (PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. It is inspired by the social behavior of bird flocking or fish schooling, where individuals (particles) move through the problem space to find the optimal solution. PSO is more suited to large-scale and multi-objective problems in land-use layout optimization. It is also relatively simple to implement and does not require gradient information, making it suitable for non-differentiable and non-linear problems. However, like some other metaheuristic algorithms, the performance of PSO can be sensitive to parameter settings, such as the number of particles, the inertia weight, and acceleration coefficients, which need to be carefully tuned [15,29]. The artificial bee-colony algorithm offers a robust and adaptive approach to land-use layout optimization, emulating the intelligent foraging behavior of honey bees to find efficient and sustainable land-use configurations [17,18]. In summary, heuristic algorithms provide efficient, robust, and flexible methods to tackle the intricate challenges of planning and allocating land resources in an optimal manner.

Among these methods, the genetic algorithm (GA) approach offers multiple advantages over other heuristic algorithms in land-use optimization. It brings a powerful set of tools to the table for land-use optimization, due to its powerful global search capabilities, parallel processing capabilities, adaptability, multi-objective optimization capabilities, and ease of implementation and adjustment [12,30]. Therefore, it is highly practical to use a GA to solve the optimal-layout problem for logistics and warehouse land in logistics scenarios.

This study aims to establish a model for the multi-objective optimization of land used for logistics and warehousing, which could help planners and administrators to evaluate and optimize layout schemes. In the context of the current study, the proposed model takes four factors (logistics demand, residential environment, traffic conditions, facility conditions, land price conditions) into account, based on spatiotemporal big data. Multiple optimization objectives in the logistics scenario are designed as the evaluation criteria and spatial guidance for the schemes, and a GA is used to efficiently solve the model. The established logistics model is applied to the layout optimization of logistics and warehouse land in Wuhan to determine the optimal solution under large-scale spatial units.

The three main contributions of this study are presented below:

- (1) Quantitative calculations and evaluations are performed on the relevant influencing factors in the spatial layout of logistics land based on spatiotemporal big data;
- (2) A model oriented toward the multi-objective optimization of logistics and warehouse land is proposed, which is solved using a GA in combination with the optimization objectives;
- (3) A case study of Wuhan city is used to demonstrate how the proposed model could effectively evaluate and optimize the spatial layout of logistics and warehouse land in the Wuhan urban development area (WUDA) to validate and show its advantages compared with other models.

## 2. Materials and Methods

### 2.1. GA–Logistics and Warehouse Land-Use Optimization Model (GA-LUOM)

#### 2.1.1. Overview of the GA-LUOM

Before introducing the proposed GA-LUOM, this section first explains several definitions and assumptions, as follows:

**Definition 1.** *The basic analysis unit is an equal-area regular grid, which was created in the study area. Containing different attributions, this could represent the different kinds of land use or some factors in the proposed model.*

**Definition 2.** The variables comprise the basic analysis unit with the land type (such as logistics and warehouse land) in the study area. In our model, a 3D  $M \times N \times K$  array was created, in which the area that could be used for logistics and warehouse land optimization was used as a variable in the GA-LUOM. In the 3D  $M \times N \times K$  array,  $K$  represents the land-use type, and  $M$  and  $N$  represent the number of rows and columns in study area.

**Definition 3.** The constant is an  $M \times N \times V$  space suitability matrix, which consists of the basic analysis unit with relevant factors that can guide or constrain the space for the optimization of logistics and warehouse land in the GA-LUOM. This was generated by multi-source data fusion processing and brought into the GA-LUOM for calculation and optimization purposes.  $V$  represents the value of relevant factors in the space suitability matrix.

**Definition 4.** An objective function is a mathematical function that is used to quantify the optimization objective based on the practical requirements. Five factors are considered in the proposed model.

**Assumption 1.** It is assumed that the scope consists of multiple basic analysis units with different land types.

**Assumption 2.** It is assumed that the total area of logistics and warehouse land could not exceed the upper limit according to the actual scenario.

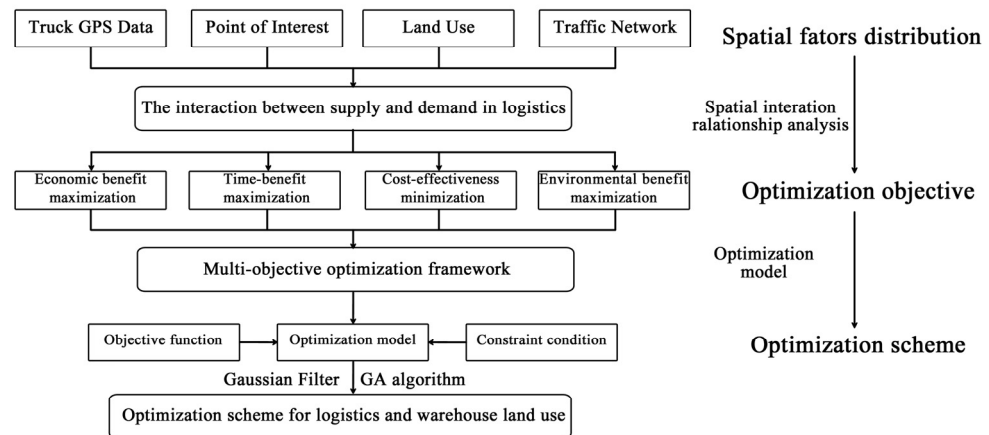
This section introduces a GA–logistics and warehouse land-use optimization model (GA-LUOM), whose aim is to find an optimal basic analysis unit layout to maximize or minimize the benefit in a given objective function. In this GA-LUOM, an equal-area regular grid was used as the basic analysis unit to construct a multi-objective logistics and warehouse LUOM [31]. It is assumed that the scope contains multiple basic analysis units, with each unit labeled as either logistics and warehouse land or another land-use type  $K$ . The study subject was expressed as a three-dimensional (3D) array, representing the basic analysis unit of land-use type in row  $i$  and column  $j$ . The basic analysis unit with the land-use type is the variable in the proposed model. This is used to be constrained and guided by the spatial factors. The relationship between supply and demand in the basic analysis units was analyzed for constructing objective functions based on multi-source spatiotemporal big data. Finally, an objective-solving method based on the non-denominated sorting genetic algorithm II (NSGA-II), which is both fast and elitist, was constructed to solve the model, and the optimization results were obtained. In the context of the current study, the GA-LUOM took freight activities into account, which made it more practical and scientific. In addition, a Gaussian filter was introduced for planners to adjust the spatial distribution of logistics and warehouse land according to specific requirements.

In this study, an NSGA-II-based multi-objective logistics and warehouse LUOM was established; the detailed process of this is shown in Figure 1 and included the following six steps:

1. Factors' influence analysis: Based on multi-source spatiotemporal data and focusing on basic analysis units, the interaction characteristics between supply and demand in logistics space were quantitatively analyzed and evaluated for different types of factors (such as economy, time, environment, and cost).
2. Objective function construction: Based on the factors' influence analysis, several factors were used to design four differentiable optimization objective functions, including economy, time, cost, and environment.
3. Constraint condition setting: There were some unchangeable land types in the study area. Therefore, the basic analysis units with unchangeable land types were not included in the model computation.
4. Optimization model construction: With the benefits of economy, time, environment, cost, and other factors as the optimization objectives, and considering the constraints of spatial land use, an optimization model for logistics and warehouse land was

constructed. It is noteworthy that the weight of each objective was according to its importance in a specific scenario [19].

5. GA-based optimization: Based on a genetic algorithm, the constructed optimization model was solved, and the optimization results were obtained.
6. Gaussian filtering: A Gaussian filter was built for smoothing the results of the basic analysis units during each iteration of the proposed model.



**Figure 1.** Flowchart of the GA-LUOM.

### 2.1.2. Factors Affecting the Demand and Supply for Logistics and Warehouse Land

In demand, freight Global Positioning System (GPS) data reflect the spatial trajectories of trucks during the logistics transportation process, and the origin–destination (OD) relationship directly reflects the spatial relationship between logistics supply and demand [32]. Therefore, determining the spatial needs of logistics based on freight OD data, which can truly reflect the spatial characteristics of the real environment and have a direct guiding role in the planning and layout of urban logistics and warehouse land, is both scientific and time-sensitive. In addition, other functional spaces in the city, such as industrial and commercial spaces, generate the sources of and influence the logistics demand and have a strong degree of spatial coupling with logistics and warehouse land.

In supply, the proposed model considers four factors, which are the residential environment, traffic conditions, facility conditions, and land price conditions. All five factors, both in demand and supply, are explained in detail as follows:

1. Logistics demand: Logistics and warehouse land is the space of logistics supply, and the active response to market demand is the primary principle of its spatial layout, which is reflected in the full coupling of supply and demand spaces. A space with a higher level of logistics demand has a greater probability of being developed as logistics and warehouse land than a space with a lower level of logistics demand.
2. Residential environment: Due to the special nature of logistics and warehouse land, the use of space can generate negative externalities, such as noise and pollution, which have a great impact on other functional spaces in the city, such as residential and leisure spaces. Therefore, in the optimized layout of logistics and warehouse land, there is a strong negative correlation between logistics and warehouse land and residential or leisure space. Therefore, this study assumed that the larger the distance of an area from the residential center, the higher its level of suitability will be for being developed as logistics and warehouse land [33].
3. Traffic conditions: Convenience accessibility is an important principle considered in logistics transportation that specifically reflects the strong dependence of logistics and warehouse land on areas with dense road networks. Therefore, in this study, the greater the road network density is, the more suitable the area is for being developed as logistics and warehouse land.



4. Facility conditions: The process of storing, transporting, and supplying logistics is strongly correlated with the water supply, the power supply, oil and gas facilities, etc. In terms of spatial relationships, the coupling between logistics and warehouse land and facility space should be considered; that is, areas with relatively complete relevant facilities are more suitable for being developed as logistics and warehouse land than other areas. While ensuring full-chain logistics operations, the construction and development costs of related facilities can be reduced.
5. Land price conditions: According to the bid rent theory of land price, the land price gradually decreases from the city center to the suburbs, which reflects the spatial characteristics of urban economic activities [34]. The relatively low level of economic output benefits of logistics and warehouse land determine its high degree of sensitivity to land prices. In general, areas with lower land prices are more suitable for being developed as logistics and warehouse land than those with higher land prices.

### 2.1.3. Objective Function

For the established GA-LUOM, which tends to be close to the actual scenario, a single optimization objective cannot fully reflect the intrinsic relationships between the development of logistics and the various factors involved. Therefore, in this study, four differentiable optimization objective functions were designed for the four aspects of economy, time, cost, and environment to generate an optimization scheme for logistics and warehouse land use.

**Economic benefit maximization:** The maximization of economic benefits is one of the most important optimization objectives in the GA-LUOM. The economic benefits in this study were reflected in the economic output resulting from the amount of logistics and warehouse land and its different spatial locations. The specific formula for this is as follows:

$$F1 : f_{gdp} = \sum_{i=1}^i \sum_{j=1}^j \sum_{k=1}^k p(i, j, k) * s(i, j, e) * e(k)$$

where  $f_{gdp}$  denotes the economic benefits of the optimal scheme,  $p(i, j, k)$  represents the land-use layout of the optimal scheme, and  $s(i, j, e)$  is the space suitability matrix with the value of the economic factor. In this study, the two aspects of the movement characteristics of freight vehicles and the agglomeration degree of industrial activities were considered and calculated as constant information for the economic effect.  $e(k)$  indicates the contribution coefficient of land-use type  $k$  to the economic benefits.

**Time benefit maximization:** In the GA-LUOM, since the time benefit is an indispensable factor in the logistics system, the spatial layout of logistics and warehouse land is guided and constrained by the time benefit to improve its operational efficiency. Therefore, the time benefit function was defined as the spatial coupling degree between the spatial layout of logistics and warehouse land and the road network density. Its specific formula is as follows:

$$F2 : f_{time} = \sum_{i=1}^i \sum_{j=1}^j \sum_{k=1}^k p(i, j, k) * s(i, j, t) * t(k)$$

where  $f_{time}$  is the time benefit of the optimal scheme,  $p(i, j, k)$  is the land-use layout of the optimal scheme, and  $s(i, j, t)$  is the space suitability matrix with the value of the time factor. In this study, the influence of urban road network density was considered and calculated as constant information of the time effect, and  $t(k)$  represents the contribution coefficient of the land-use type to the time effect.

**Cost-effectiveness minimization:** In the logistics system, the cost-effectiveness considered in the GA-LUOM is based mainly on the minimization of facility construction and land prices. After taking into account the space suitability of relevant elements, the specific formula for this is as follows:

$$F3 : f_{cost} = \sum_{i=1}^i \sum_{j=1}^j \sum_{k=1}^k p(i, j, k) * s(i, j, c) * c(k)$$

where  $f_{cost}$  is the cost-effectiveness of the optimal scheme,  $p(i, j, k)$  is the land-use layout of the optimal scheme, and  $s(i, j, c)$  is the space suitability matrix considering the cost-effectiveness factor. In this study, the land value and spatial distribution of points of interest (POIs) were considered and used as constant information of the cost effect for quantitative assessment, and  $c(k)$  represents the contribution coefficient of the land-use type and the level of cost-effectiveness.

Environmental benefit maximization: Citizens pursue a high-quality living environment [35]. Therefore, the environmental benefits of the logistics system are measured in the GA-LUOM based on the distance of the system from the residential center, and this specific formula is as follows:

$$F4 : f_{live} = \sum_{i=1}^i \sum_{j=1}^j \sum_{k=1}^k p(i, j, k) * s(i, j, l) * l(k)$$

where  $f_{live}$  represents the environmental benefits of the optimal scheme,  $p(i, j, k)$  is the land-use layout of the optimal scheme, and  $s(i, j, l)$  is the space suitability matrix with the value of the environmental factor. In this study, the space suitability matrix is realized by considering the density of residential areas, and  $l(k)$  represents the contribution coefficient of the land-use type to environmental benefits.

A weighted combination of  $F1$ ,  $F2$ ,  $F3$ , and  $F4$  could be expressed as a maximized  $U$  (referred to as  $F5$ ):

$$F5 : U = a * f_{gdp} + b * f_{time} + \frac{c}{f_{cost}} + d * f_{live}$$

where  $a$ ,  $b$ ,  $c$ , and  $d$  are the weights of all objectives.

#### 2.1.4. Constraint Conditions

To ensure conformity to all types of standards in the actual scenario, during the operation of the model, strict control constraints were imposed on the unchangeable land types in the study area, such as military areas, ecological protection areas, and other areas. At the same time, this study used the scale of logistics and warehouse land as a constraint to limit the optimization process and results.

#### 2.1.5. GA-Based Optimization

A GA is an algorithm that allows for an optimal solution, with an adaptive ability and global search, to be obtained, and it is formed by simulating the mechanism of biological evolution in nature. A GA uses each set of possible solutions to an optimization problem as the initialization population: each solution corresponds to a chromosome, chromosomes are paired according to their level of fit, and the next generation is generated by controlling the crossover and mutation rates. The algorithm repeatedly iterates until the termination condition is met; then, the algorithm breaks out of the loop and generates an optimal solution. In land-use optimization, it brings a powerful set of tools to the table due to its strong global search capabilities, parallel processing capabilities, adaptability, multi-objective optimization capabilities, and ease of implementation and adjustment. The NSGA-II framework emphasizes non-dominated sorting to find the optimal solution, which is more advantageous in multi-objective optimization than other frameworks [36,37].

In this study, the spatial distribution of each land-use type within the study area was processed as an individual in the algorithm; that is, each logistics land-use layout scheme was used as an individual and encoded as a set of numbers, i.e., the chromosomes for processing. A variety of logistics land-use layout schemes were used to form multiple individuals, thus forming a population. The individuals in the population were traversed to determine the dominant and non-dominant relationships among all individuals to achieve

the sorting and ranking of all of these individuals in the population. After sorting, the tournament selection was used to select  $K$  individuals, the levels of fit of these selected individuals were calculated, and the individual with the optimal fit level was put into the offspring population. At the same time, considering crossover and mutation, new individuals were continuously generated. In the crossover operation, two individuals were selected in the parent generation, and the partial genomes of these two individuals were exchanged according to a certain probability to generate two offspring that entered the offspring population. This study used simulated binary crossover (SBX), and the proportion of parent individuals participating in the crossover was controlled by setting the crossover probability. After the crossover operation, to maintain species diversity and enhance the local search ability of the algorithm, the mutation operation was used to mutate some chromosomes in an individual to other possible values at a certain probability. A mutation probability that was too low would make it difficult to maintain species diversity, while a probability that was too large would lead to too much randomness in the search process, and in this study, mutation probability was used to adjust the optimization results. Through the above operations, a population of offspring was generated and continued to evolve iteratively. Individuals were selected according to Pareto ranking from high to low, and the iteration continued. After reaching the necessary number of iterations, a set of Pareto optimal solutions of multiple-objective functions was obtained and, thus, so was the optimal scheme.

#### 2.1.6. Gaussian Filtering

To avoid a great degree of noise in the optimization results, a filter was necessary for smoothing the results of the basic analysis units during each iteration of the proposed model. In this study, the Gaussian filter was chosen to ensure that the generated solution was in line with the real scenario. The Gaussian filter is a type of linear smoothing filter, the template of which can be obtained by discretizing the two-dimensional (2D) Gaussian function. The Gaussian filter uses a Gaussian kernel to convolve the data, which can effectively blur the noise while also preserving the overall structure. It can be applied in both spatial and frequency domains, making it versatile for different types of data processing tasks. At the same time, this filter tends to preserve important features of the data. Therefore, it is very applicable for smoothing the basic analysis units in the study area compared with other methods.

The smoothing is controlled by adjusting the standard of the Gaussian kernel. The specific formula for this is as follows:

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

where  $x$  and  $y$  are the locations of basic analysis units, and  $\sigma$  is the smoothed mean. The larger the value of  $\sigma$ , the more concentrated the distribution.

#### 2.2. Study Area and Data

Wuhan is located in the central part of China. With the construction of a “five-type” (port, dry port, airport, production and service, and business service) national logistics hub, the logistics industry has become an important pillar of industry in Wuhan. The efficiency of logistics operations continues to improve, and the network agglomeration effect is apparent, which is of important strategic significance for accelerating the construction of a central city, building a national trade and logistics center, and optimizing the layout of logistics and warehouse land in Wuhan.

This study used the WUDA, i.e., the spatial range consisting of the main urban area and six new city groups (Figure 2) with a land area of 3261 km<sup>2</sup>, as defined in the Wuhan City Master Plan (2010–2020), as the study area.



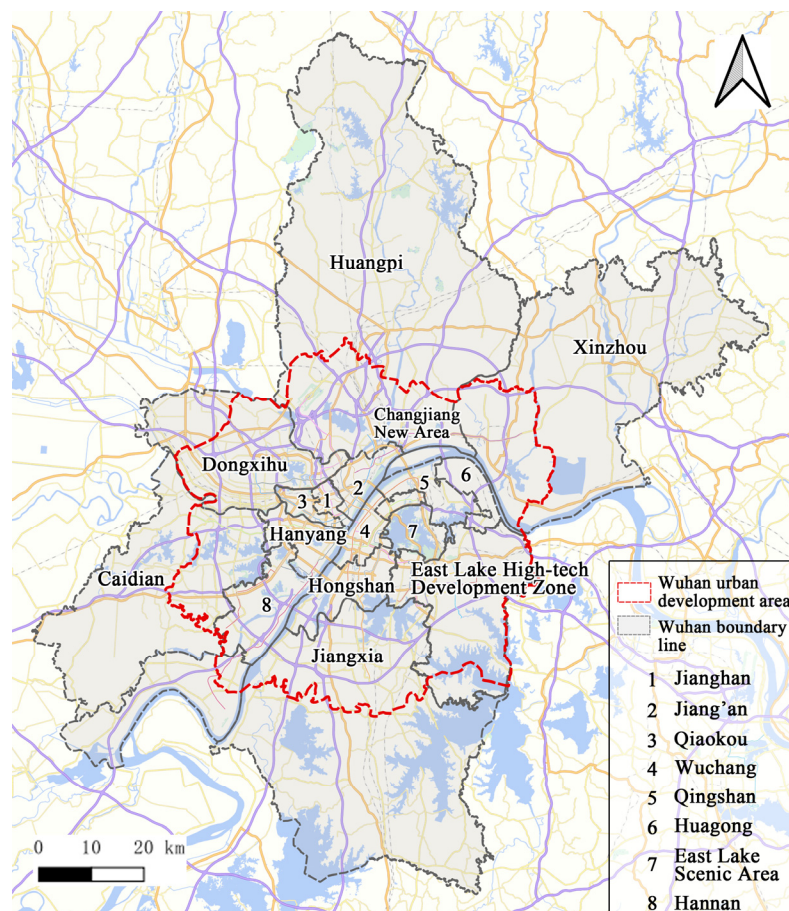


Figure 2. Overview of the study area.

The data used included vector data, raster data, and other data. Vector data included the land-use, freight GPS, road traffic network, and administrative boundary data of the WUDA; the raster data included the remote-sensing image data of Wuhan; and the other data included the economic development data of the logistics industry and the tabular data of relevant elements (Table 1).

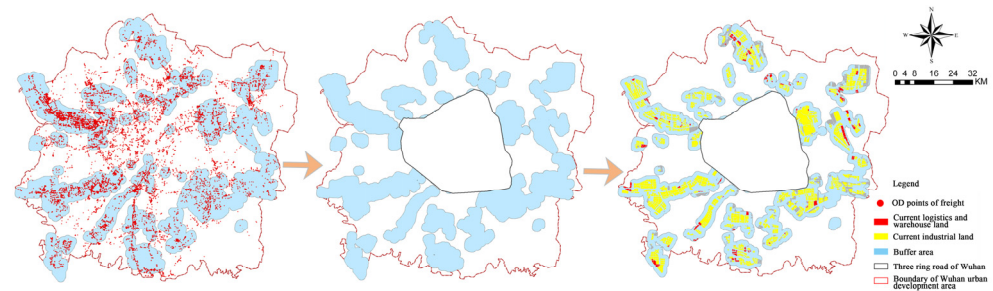
Table 1. Descriptions of the data.

Data Type	Data Name	Data Contents
Land use	Current land use	Land-use data of the WUDA
Logistics element	GPS data	Truck GPS data
Traffic element	Road network	Current roads in the WUDA
Administrative division	WUDA boundary	The area of the WUDA Facilities
Other	POI data	House prices Residential community

### 2.3. Data Processing

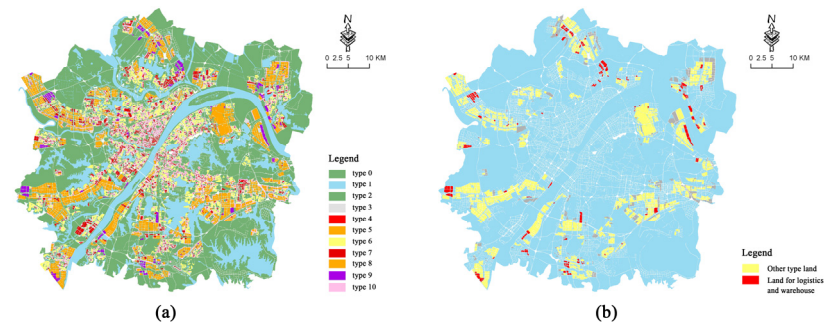
#### 2.3.1. Variable Data Processing

Through the processing of the truck GPS data, the OD points reflecting the freight space demand were extracted. From the research perspective of logistics and warehouse land, there was a mismatch between the spatial supply and demand in Wuhan's logistics system. After a buffer zone was created at 1 km from industrial land, most of the logistics space demand points were covered in the buffer zone, with the coverage rate reaching 72.8%. The spatial area covered by the buffer zone basically reflects the logistics space demand of the WUDA (Figure 3).



**Figure 3.** Flowchart of varying regional identification.

Considering the urban development strategy of Wuhan, the area covered by the buffer zone outside the Third Ring Road was used as the spatial base, and various controlled land uses, such as military land areas, solid-line control areas, and dotted-line control areas, were defined as restricted areas. Other land uses were used as variables in the GA-LUOM for the WUDA, and the variable data were stored in the form of a raster consisting of  $2349 \times 2235$  basic analysis units, with a side length of 30 m (Figure 4). This scenario was considered the current situation and was set as the initial scenario of the optimization model.

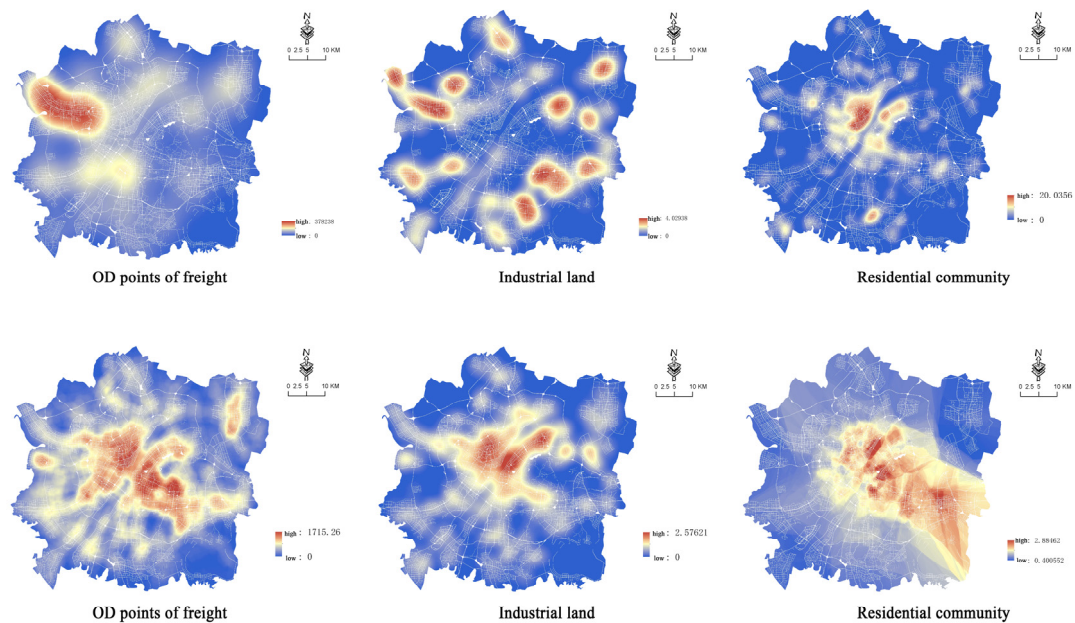


**Figure 4.** Processing results of variable data: (a) current land-use map and (b) current variable data.

### 2.3.2. Constant Data Processing

All kinds of constant data are directly related to the optimization objective function of the model and play a guiding and constraining role in the process of the layout optimization of logistics and warehouse land, directly affecting the optimal solution. Therefore, the processing and analysis of various constant data are important for model construction and solving, and the specific calculations of these constants are shown in Figure 5.

**Economic-benefit-related constants:** With the truck GPS data, the OD points of each freight trip could be extracted by data cleaning and trip clipping. In data cleaning, the error records (such as location error or speed error) were deleted. Then, the trajectory of each truck was clipped into several trips based on the dwell times around a point. This study defined a time interval threshold of 1 h. If a freight trip extracted from heavy truck GPS data contained two successive records separated by a time interval of more than 1 h, that freight trip was discarded [38]. Based on the results of the trip clipping, a kernel density analysis was performed on the freight OD points to determine the optimal layout of logistics and warehouse land in the model optimization process and to achieve the spatial matching of supply and demand. At the same time, a density analysis was performed on the industrial agglomeration in the WUDA to constrain the spatial layout of logistics and warehouse land and avoid the situation in which logistics and warehouse land replaces high-output-value industrial land in the process of solving the model.



**Figure 5.** Processing results for the constant data.

**Time-benefit-related constants:** Based on the vector data of current roads from OSM (OpenStreetMap) in Wuhan and a linear density analysis of the road network of the WUDA, the process of optimizing logistics and warehouse land use tended to favor a regional layout with higher-density and better traffic conditions, which reflected the spatial coupling relationship between the logistics system and transportation conditions under the time-benefit orientation.

**Cost-effectiveness-related constants:** Based on the POIs of facilities in the WUDA, the kernel density of facilities was calculated. The facility construction in the WUDA could guide the spatial layout of logistics and warehouse land. Planning and laying out logistics and warehouse land in areas where facilities are well established could reduce the costs associated with the logistics operation system. Based on the POI data of housing prices in the WUDA, the housing price within the WUDA was fitted by using the kriging spatial analysis tool to reflect the land price in this region. To reduce construction costs, logistics and warehouse land tended to be distributed in areas with lower land prices.

**Environmental-benefit-related constants:** Based on the data of house prices in the WUDA, a density analysis was performed on the aggregation of residential points in the study area. The aggregation of residential points could generate negative effects when it was too close to the land used for logistics and warehousing. Thus, the result of this constant had a strong constraining effect on the spatial layout.

### 3. Results

This study designed three scenarios to represent different weighting schemes in  $F5$  and the filter. Under these three scenarios, the results also differed, which could indicate the improvement of the GA-LUOM.

**Scenario 1:**  $a = 0.25, b = 0.25, c = 0.25, d = 0.25$  in  $F5$ , and  $\sigma = 10$  in the Gaussian filter. This scenario dealt with a combination of the objectives of economic benefit maximization, time benefit maximization, cost-effectiveness minimization, and environmental benefit maximization.

**Scenario 2:**  $a = 0.25, b = 0.25, c = 0.25, d = 0.25$  in  $F5$ , and  $\sigma = 13$  in the Gaussian filter. This scenario was designed to show the influence of Gaussian filtering on the optimization solutions. With the higher value of  $\sigma$ , the layout of logistics and warehouse land would be more concerned in the result of this scenario.



Scenario 3:  $a = 0.33$ ,  $b = 0$ ,  $c = 0.33$ ,  $d = 0.33$  in  $F5$ , and  $\sigma = 10$  in the Gaussian filter. The effect of the freight activity was ignored in this scenario compared with Scenario 1, which could demonstrate the important of this factor.

Two constraint conditions were handled in the GA-LUOM across all three scenarios. The first constraint condition was that the total area of logistics and warehouse land did not exceed  $42.5 \text{ km}^2$ , which was set in the Wuhan City Master Plan (2010–2020). The second constraint condition was that the basic analysis units with unchangeable land types (including military areas, ecological protection areas, and capital farmland areas) were not calculated in the proposed model. With these two constraint conditions, optimization schemes for logistics and warehouse land use were sought under three scenarios. During the running of the model, the number of chromosomes was set to 100, the maximum number of iterations was 200, the crossover rate was 0.2, the mutation rate was 0.1, the resampling rate was 4, and the running time of the model was 644.92 s. All of the computational tasks were single-threaded and implemented on a desktop (six Intel(R) Core (TM) processors with CPU i7-6850K @ 3.60 GHz, 32G of RAM, and a 64-bit operating system, Intel, Santa Clara, CA, USA). The GA model was developed using Python3.8. If a graphical processing unit (GPU) was used, then the running time of the model was further decreased.

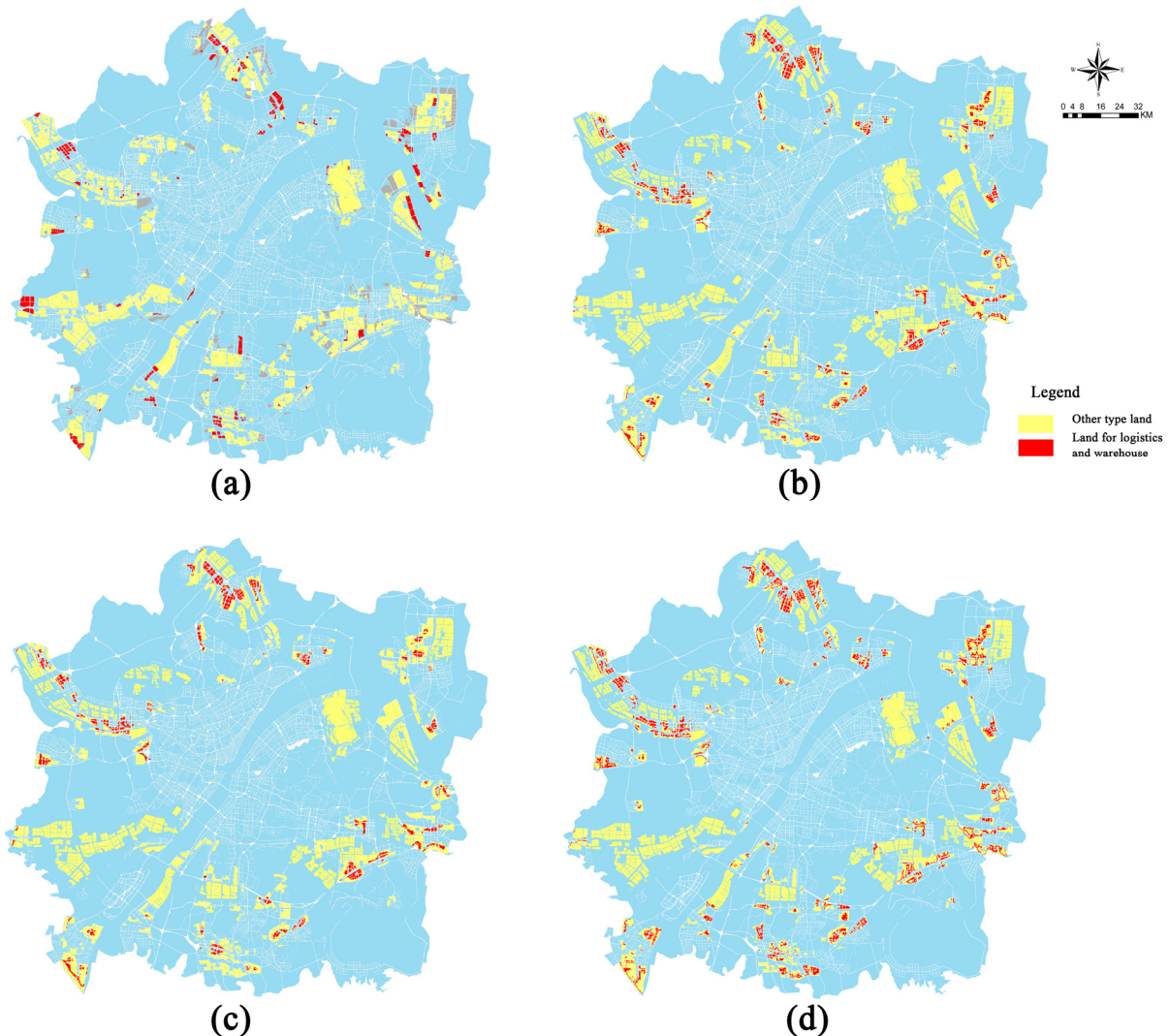
After running the model in three scenarios, multiple optimal solutions were found (Table 2), such as schemes b, c, and d in Figure 6, and the optimization schemes achieved greater improvements in terms of meeting each objective, which verified the feasibility of the model. In the original plan, the logistics and warehouse land was distributed mostly in a centralized manner and in the northern part of Hankou, Dongxihu District, and Yangluo International Port. According to the optimization scheme shown in Figure 6b, the distribution of logistics and warehouse land was relatively scattered, with increases in the northern part of Hankou, the Dongxihu District, and the eastern part of the Optics Valley, and the level of distribution of logistics and warehouse land in Yangluo International Port and Hanyang District was slightly reduced. According to the results shown in Figure 6c, the overall layout of logistics and warehouse land was similar to that of scheme b, with decreases only in some fragmented land parcels. Comparing the detailed information in Table 2, the time benefit of scheme a was much larger than that of scheme b. This finding suggests that planners and logistics managers should further improve the supporting transportation facilities around Yangluo International Port and Hanyang District.

**Table 2.** Optimization schemes for logistics and warehousing land use under scenarios with different preferences.

Optimization Scheme	Economic Benefit	Time Benefit	Cost-Effectiveness Benefit	Environmental Benefit
Original scheme a	6366.92	−85,948.97	26,063.80	−89,014.98
Optimization scheme b	14,829.16	−135,322.05	161,747.44	−283,007.23
Optimization scheme c	14,709.83	−135,265.30	161,681.31	−282,753.84
Optimization scheme d	4152.41	−161,739.50	203,861.22	−69,079.55

To validate the advantages of the proposed model, Scenario 3 was designed. Multiple optimal solutions were found in scheme d in Table 2 using the GA-LUUM. In Scenario 2, the spatial guidance effect of the freight OD (origin–destination) points on the layout of logistics and storage land is not considered. Therefore, the GA-LUOM lacked the conditions of spatial matching between the logistics supply and demand during the optimization process. According to the Scenario 2 result, the distribution of logistics and warehouse land area was more scattered in the study area compared with that observed in Scenario 1. This land appeared in most zones, such as the northern part of Qingshan District, Caidian District, etc. At the same time, the distance between the logistics and warehouse land areas was also not very good. This optimal solution could not be sufficient to achieve large-scale economy and combined effects. With it not matching the real spatial demand very well,

this result might lead to the waste of urban land resources. Comparing the results between Scenario 1 and Scenario 2, it is indicated that freight activity is an important factor to consider in logistics and warehouse land planning. When the effect of freight activity (such as freight OD points) was not considered in our analysis, the economic benefit performance fell significantly and the demand for freight was difficult to meet.



**Figure 6.** Optimization schemes for logistics and warehousing land use. (a) shows the spatial layout of original scheme a; (b–d) represent the distributions of logistics and warehousing land use according to optimization scheme b to d.

Compared with optimization scheme b from Scenario 1, optimization scheme d indicates that the economic benefit experienced a significant decline. Although the time and cost-effectiveness benefits were better, the overall optimization performance was obviously worse than that of optimization scheme b. Therefore, considering the factor of the economy is very important in the proposed model. Incorporating the spatiotemporal characteristics of freight activities could effectively enhance the scientific validity of the optimization solution. And urban planning or logistics management personnel need to give more priority and attention to these activities.

Under Scenarios 1 and 2, the effect of the Gaussian filter in the optimization process could be seen through the results of optimization scheme b and c. Based on the results in Table 2, there was no noticeable gap in optimization scheme c compared with optimization scheme b. At the same time, the spatial layout of logistics and warehouse land became more



concentrated. Thus, the Gaussian filter provides a powerful tool for planners to adjust the spatial distribution of land use without significantly deteriorating the overall performance.

#### 4. Discussion

In this study, a multi-objective optimization model that fits the actual logistics and warehouse land-use optimization scenario was established; the real, complex problem was abstracted as a scientific mathematical model; and the model was solved using a GA to obtain a solution that met the actual land-use optimization rules. A case study of Wuhan city was conducted to illustrate how the proposed model can evaluate and optimize the layout of logistics and warehouse land. The results show that in solving the logistics and warehouse land optimization scenario with multiple optimization objectives and a large number of spatial units, the GA could obtain high-quality solutions. In addition, to avoid the discrete randomization problem that occurs in a GA's optimization process, a Gaussian filter was introduced to smooth the solutions during the solution process to generate results that were more in line with the land-use optimization rules. During the operation of the model, the balance between different optimization objectives was considered, and the model comprehensively considered the impacts of time, cost, and the urban built environment while improving the economic benefits of logistics.

The WUDA was used as the study area to validate the accuracy and efficiency of the proposed model under logistics and warehouse land optimization scenarios. The model took economic benefits, time benefits, cost benefits, and environmental benefits as the optimization objectives. By setting relevant constraint conditions and forbidden areas, the model used its GA to perform a space search on the possible optimization schemes, and multiple Pareto optimal solutions were found. Compared with the original land-use scheme, the optimization results showed some improvements in the land-use mode. The spatial layout of logistics and warehouse land in Wuhan was optimized through the combination of local concentration and partial dispersion. In terms of the measurement of the optimization objectives, the schemes obtained with the GA were significantly improved in all of the objectives, which could be regarded as a planning reference for the spatial layout of logistics and warehouse land use in the future and could have strong reference significance for planning decision-makers.

At the same time, the optimization results were strongly correlated with the sampling rate of the raster data and the standard deviation of the Gaussian filter. In the original land-use raster data of Wuhan city, there were too many spatial units, and the level of computational complexity of the model was high. Therefore, this study compared the running time of the model under different sampling rates to determine the sampling ratio that provides a fast computational speed and high-quality results. In addition, the standard deviation of the Gaussian filter was also directly related to the quality of the optimization schemes.

The model proposed in this study can be used to analyze and evaluate the layout of logistics and warehouse land. And an efficient and reliable tool is provided in this study for layout optimization to assist planners and administrators in decision-making. The improvements of the proposed model were achieved in two aspects through designed scenarios. First, in the context of the current study, the GA-LUOM took freight activities into account, which made it more practical and scientific. Second, the Gaussian filter was introduced to enable planners to adjust the spatial distribution of logistics and warehouse land use according to specific requirements. However, some limitations exist in the proposed model. The first limitation is that the weights of objectives in different scenarios were often set based on the researcher's experience, which would lead to insignificant optimization effects. Users need to find the optimal weight combination through multiple attempts. The second is that the GA took a long time to converge to a solution, which could be a drawback for time-sensitive applications. Therefore, the proposed model could improve from two perspectives: Firstly, further study is needed to determine how to obtain better weight combinations based on different requirements. In addition, optimizing the

model structure and parameters to enhance operational efficiency is also an important aspect to explore in future work.

## 5. Conclusions

With the transformation of production methods in modern cities, product production and distribution show strong spatial heterogeneity, followed by large-scale growth in terms of urban logistics demand. However, the supply of urban logistics and warehouse land and the actual logistics demand often bring about spatial dislocation. The planning and layout of logistics and warehouse land still rely mainly on the qualitative and subjective judgment of planners, making it difficult to match the supply and demand of logistics space. In the era of big data, the spatiotemporal big data of multi-source logistics can fully meet real and effective logistics needs, and data-driven quantitative analysis methods can effectively determine the scientific spatial layout of logistics and warehouse land, thus providing strong support to planners in the planning decision-making process.

In this study, a large-scale logistics and warehousing land-use optimization problem was established as a differentiable mathematical model by constructing the GA-LUOM, and the GA was used to solve this model with the optimization objectives of achieving economic, time, cost, and environmental benefits. The model results for the practical case of Wuhan city show that the model can generate high-quality optimization schemes in a relatively short time and has a certain planning value for different application scenarios generated by different needs.

This study's main findings according to the results can be summarized as follows:

1. According to the comparison between optimization schemes b and d, it is indicated that incorporating the spatiotemporal characteristics of freight activities can effectively enhance the scientific validity of the optimization solution.
2. The analytical results of schemes b and c show that concentrating the layout of logistics and warehouse land could reduce costs to some degree.
3. Compared with scheme a, the optimal solution of scheme b revealed that laying out logistics and warehouse land around large freight hubs does not significantly reduce costs or enhance economic benefits.

In the future, this optimization model could be improved in terms of actual applications, factors, and model performance. First, due to the complexity of urban logistics land-use optimization, more realistic scenarios should be considered to validate the model's reliability and generalizability. For example, the overall carrying capacity of a city's logistics operations should be considered, the scale of logistics and warehouse land should be determined in combination with the urban development strategy, the total amount should be constrained by a threshold in the model, and some realities, such as the current construction status of logistics and warehouse land and the limitations of ownership management for land-use type conversion, should also be considered. Second, more factors could be taken into account in the model, such as carbon emissions, traffic safety, and the fairness of logistics services. And, regarding the influencing factors related to the characteristics of logistics activities, the weight characteristics under various objectives also need further in-depth study. Third, in terms of technological and methodological aspects, the methods used for calibrating the relevant parameters require further research to help planners to obtain better solutions. Furthermore, with the development of online and offline business models, future research should focus on the construction of a life logistics model to further improve the quality of life of urban residents and achieve the refined governance of urban space development.

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