# A HYBRID MULTI-OBJECTIVE MODEL FOR MULTI-STORY WAREHOUSE DESIGN

*A case study in Shenzhen*

YI WEN[1], WEI YE[2] AND GANG YU[3]
[1,3]*School of Architecture, Harbin Institute of Technology, Shenzhen,*
[2]*School of Engineering Technology, Purdue University.*
[1]*23b356003@stu.hit.edu.cn, 0009-0005-9694-5627*
[2]*ye375@purdue.edu, 0000-0001-9341-2212*
[3]*yuarch@hit.edu.cn, 0000-0002-9352-4385*

**Abstract.** The thriving on-demand delivery economy and the increasing focus on addressing the global environmental crisis have spurred the need for efficient and sustainable logistics facilities in urban central areas. This paper delves into the optimization of multi-story logistics warehouse design in Shenzhen, China. Based on comprehensive investigations of existing multi-story warehouses in Shenzhen, the study proposes a hybrid computational model of integer programming and NSGA-II tailored for the generation and optimization of multi-story warehouse general layout design. The prototype, aimed at enhancing efficiency and sustainability, translates these concepts into attainable goals of optimizing land utilization, construction cost, and transportation distance. By addressing multi-objective challenges in the design process, the prototype's effectiveness is validated through a real-world case study. This paper seeks to offer a pragmatic approach to designing cost-effective and resilient multi-story logistics warehouses in the long term, applicable in both Shenzhen and other densely populated urban centers. The insights derived from this study may contribute to the ongoing discourse on optimizing logistics in dynamically evolving industrial landscapes.

**Keywords.** Logistics warehouse design, multi-story warehouse, generative design, multi-objective optimization, efficiency, sustainability, integer programming, NSGA-II.

## 1. Introduction

In the past decade, the evolution of supply chain and automation industry dynamics has catalyzed a “vertical shift” in the logistics landscape(Aderneck, 2020; Lim & Park, 2020; Xiao et al., 2021). The surge in e-commerce and the increasing demand for last-mile delivery underscore the vital role of high-capacity logistics facilities in metropolitan areas. In this context, the strategic design of efficient and sustainable

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multi-story logistics warehouses has emerged as a significant topic. Given the fact that salient constraints on land availability(Yuan & Zhu, 2019; Xiao et al., 2021) in monocentric metro areas has less impact in previous studies(Sakai et al., 2015; Giuliano & Kang, 2018; Heitz et al., 2020), this paper delves into the critical domain of multi-story logistics warehouse design in Shenzhen, China.

Researchers have proposed a wide range of multi-story warehouse layout optimization strategies. At the urban scale, current studies have presented the large-scale, multi-tenant and mixed-use logistics solutions in dense urban areas to address space constraints(Xiao et al., 2021; Buldeo Rai et al., 2022). Concerning the need for sustainability, Xiao et al. (2021) has highlighted the sustainable logistics land use patterns in Shenzhen, whereas other studies have also suggested green logistics transportation(Colicchia et al., 2013; Ploos van Amstel et al., 2021). At the facility scale, new heuristics based on GA(Zhang et al., 2002) or its hybrids(Zhang & Lai, 2006) have been developed to tackle multiple-level warehouse layout problems and meet the need for logistics automation. However, the perspective of architectural design of multi-story warehousing buildings has not been adequately studied yet.

Integer programming (IP) is a widely applied mathematical optimization technique in the field of architecture. Previous studies have been conducted to solve the problems including plan layout(Keatruangkamala & Sinapiromsaran, 2005) and transportation network design(Hua et al., 2019). On the other hand, non-dominated sorting genetic algorithm II (NSGA-II) was tailored to cope with multi-objective optimization more effectively(Coello Coello, 2006), which has been used to explore high-performance layout possibilities(R. Wang et al., 2021; Wu et al., 2023). While prior applications of either approach are ample, there are relatively limited researches on combining IP and NSGA-II in layout optimization(Lv & Wang, 2020).

In response to the shortage, this paper proposes a generation and optimization prototype model that integrates IP and NSGA-II. Aiming to provide multi-objective solutions for optimizing multi-story warehouse general layouts, this paper addresses the requirements of efficiency and sustainability from the perspective of architectural design. By presenting a real-world case study in Shenzhen, this research tries to offer insights applicable to regions with similar land use patterns.

## 2. Methodology

The study employs a synergistic approach, integrating IP and NSGA-II, to optimize layout configurations. IP is known for its efficiency in handling large-scale problems with reduced computational time complexity. On the other hand, NSGA-II, excels in addressing multi-objective optimization problems. By combining the precision and efficiency of IP with the multi-objective optimization prowess of NSGA-II, the study aims to achieve an optimal layout configuration that balances the benefits of both methodologies.

The methodology of this study can be divided into four parts: 1) Input and transformation of real-world information; 2) Establishment of a mathematical model for optimization objectives; 3) Generation of most occupied layouts with IP; 4) Muti-objective optimization to find the best actual layout. The methodology is shown in Figure 1 and further explained in the following.

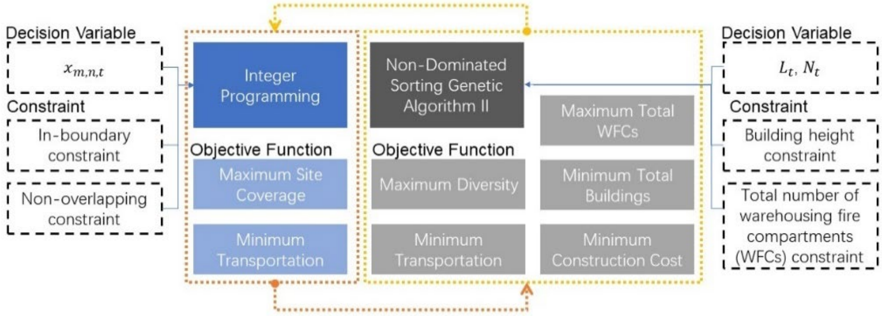


*Figure 1. Methodology*

## 2.1. INPUT AND TRANSFORMATION

### *2.1.1. Processing of Given Data*

The processing of basic data involves a three-step procedure. First, a 2D grid coordinate system is established, with the subdivision precision aligned with the standard column spacing of the warehouse (12m). Second, the geometric parameters of the site are input and gridded as a computational domain. Third, warehouse plans are transformed into a series of warehouse templates (WTs) comprising with warehousing fire compartments (WFCs), ramp units (RUs), loading bay and spacing (elaborated further in Section 3.1). Given data and decision variables are declared as follows.

Given data:

- $G_h, G_w$ are the length and width of the grid.
- $h_0, w_0, l_0$ are the length, width and single storey height of a single fire compartment
- $S$ is the set of the site grid $S = \{i, j | 0 < i \leq G_h, 0 < j \leq G_w\}$.
- $H_t, W_t$ are the length and width of template $t$, respectively.
- $s_i, b_j$ are additional constraints representing the index of available grids for rows and columns, respectively.
- $T$ is the set of $n$ types of WTs, $T = \{t_1, t_2, \ldots, t_n\}$.
- $(i_0, j_0)$ is the fixed reference point representing the site entrance.
- $L_0$ is the maximum number of building storeys.
- $M_t$ is the number of WFCs of each template $t$.
- $\text{Max\_}total$ is the maximum number of total warehousing fire compartments.
- $Price$ represents the given construction cost data.

Decision Variables:

- $x_{m,n,t}$ is a binary variable that equals 1 if the top-left corner of template $t$ is placed at cell $(m, n)$ in the grid, and 0 otherwise.
- $L_t$ the number of storeys of actual placed template $t$.
- $N_t$ the total number of actual placed template $t$.

### *2.1.2. Space Constraints*

The constraints should be added to the model for placing templates on the grid, considering the dimensions of both the grid and the templates, as well as specific constraints defined by arrays $s$ and $b$.

1. In-boundary constraint

Restrict placement in last rows and columns:

$$x_{i,j,t} = 0,\ \forall i \in \{G_h - H_t, \dots, G_h\}, j \in \{G_w - W_t, \dots, G_w\} \quad (1)$$

Row-based restrictions using s:

$$x_{i,j,t} = 0, \forall i \in \{0, \dots, G_h - H_t\}, j \in \{\max(0, \min(s_i, s_{i-1+H_t}) - W_t), \dots, G_w\} \quad (2)$$

Column-based restrictions using b:

$$x_{i,j,t} = 0, \forall j \in \{0, \dots, G_w - W_t\}, i \in \{\max(0, b_{j-1+W_t} - H_t), \dots, G_h\} \quad (3)$$

2. Non-overlapping constraint

The key is to ensure that each cell $(i, j)$ in the grid is covered by at most one part of any template, and this is determined by the position of the top-left corner of the templates and their dimensions.

$x_{m,n,t}$ is indicating whether the top-left corner of template $t$ is placed at cell $(m, n)$. $m, n$ iterate over the potential top-left corner positions of the templates that could cover cell $(i, j)$.

$$\sum_{t\in T} \sum_{m=\max(0,i-H_t)}^{\min(i,G_h-H_t)} \sum_{n=\max(0,j-W_t)}^{\min(i,G_w-W_t)} x_{m,n,t} \leq 1,\ \forall i \in \{0, \dots, G_h\}, j \in \{0, \dots, G_w\} \quad (4)$$

3. Building height constraint

According to the prescribed warehousing storey height (8m) and the baseline height (24m) for multi-story buildings, a multi-story warehouse has a minimum of 3 storeys.

$$3 \leq L_t \leq L_0 \quad (5)$$

4. Total number of warehousing fire compartments constraint

The total number of WFCs is constrained by the site area and the prescribed floor area ratio.

$$\sum_{t\in T} L_t M_t N_t \leq \max\_total \quad (6)$$

## 2.2. MATHEMATICAL MODEL ESTABLISHMENT

Multi-story warehouses, as opposed to their traditional single-story counterparts, are characterized by their occupation of denser urban spaces, elevated floor-to-ceiling heights, and enhanced spatial efficiency, promoting sustainable land usage. These structures facilitate optimized transportation networks, potentially diminishing transit distances, curtailing logistical expenditures, and contributing to a reduction in carbon emissions. This research quantitatively translates these efficiency and sustainability imperatives into measurable objectives: land utilization, construction cost, and transportation proximity. Land utilization is further disaggregated into planar density and diversity, as well as vertical intensification metrics. Accordingly, a total of six distinct objective functions are established.

1.Max Site Coverage: The strategy optimizes planar density by employing a stochastic template filling method to determine the maximum feasible WFCs on the ground plan, ensuring optimal long-term land use efficiency.

2.Max Diversity: Based on the candidates derived in the preceding step, this objective ensures diverse warehouse scales within the site by selecting the results featuring the richest types of WTs. This approach is designed to enhance the long-term profitability of warehouse operations and the overall land utilization value.

3.Max Total WFCs: The aggregate count of WFCs, distributed across all levels, directly correlates with the storage capacity of the land, where an increase in WFCs within predetermined bounds augments the overall storage rate.

4.Min Total Buildings: The vertical intensification is evaluated through randomized allocations of storeys to WTs, conforming to regulatory height and floor area ratio limitations, aiming to minimize the count of buildings.

5.Min Construction Cost: Estimated construction expenses are derived from predefined pricing datasets, providing a cost framework for the evaluation of design alternatives.

6.Min Transportation Distance: An ideal logistic layout is characterized by its succinct transportation network, with the aggregate transportation distance minimized across all levels, excluding pedestrian traffic considerations. The overall transportation distance comprises 1) the distance from the site entrance to the buildings and 2) the distance within the buildings, with the former minimized using linear programming, and the latter minimized with NSGA-II.

## 2.3. IP LAYOUT GENERATION

We first employ IP to address the objectives of site coverage and transportation distance, involving the variable $x_{m,n,t}$ and the constraints expressed by Eqs. (1)-(4).

### *2.3.1. Maximum Site Coverage*

The generation of general layout candidates starts from maximizing site coverage, where the variables under consideration are the types and quantities of WTs. The primary objectives include 1) maximizing the number of WFCs on the site and 2) increasing the quantity of WTs containing more WFCs.

While IP would yield a single optimal solution for these objectives, the prototype should provide a comprehensive set of planar arrangements for screening during the early stages to better align with real-world scenarios. Therefore, we transform these two objectives into constraints based on practical considerations and generate all solutions meeting these criteria. The result contains a set of layouts that meets the maximum site coverage requirement.

### *2.3.2. Minimal Transportation Distance from the Site Entrance*

The transportation distance from the site entrance to the buildings is minimized in the IP model. The distance $Dis_{m,n,t}$, for a template $t$ placed at position $(m, n)$ is calculated as:

$$Dis_{m,n,t} = |m - (i_0 - H_t)| + |n - (j_0 - W_t)| \quad (7)$$

This represents the distance from the bottom-right corner of the placed template $t$ to the reference point $(i_0, j_0)$.The objective is to minimize the total distance of all placed templates from the entrance:

$$min \sum_{t \in T} \sum_{m=0}^{G_h} \sum_{n=0}^{G_w} Dis_{m,n,t} * x_{m,n,t} \quad (8)$$

The result is an integrated solution that optimally achieves maximum site utilization while also minimizing the transportation distance between the site and the constructed facilities.

### 2.4. MULTI-OBJECTIVE OPTIMIZATION

In the optimization phase, NSGA-II is employed to search for the Pareto Fronts. Based on the principles of NSGA-II, the multi-objective optimization process can be described as follows.

To enhance computational efficacy and maintain the integrity of integer constraints post-genetic operations, we refined the genetic algorithm component within NSGA-II. This refinement ensures that the resultant offsprings, following crossover and mutation events, remain confined to the predefined integer bounds. The decision variables in NSGA-II, are $L_t$, $N_t$, which are both integer variables with a given range. the range of $L_t$ is from building height constraint. The result from Max Site Coverage can be used as an indicator for the range of $N_t$. The constraints in NSGA-II are expressed by Eqs. (5) and (6).

The objectives in NSGA-II are:

1.Max Diversity: $\max \sum_{t\in T}[N_t = 0]$ (9)

2.Max Total WFCs: $\max \sum_{t\in T} L_t M_t N_t$ (10)

3.Min Total Buildings: $min \sum_{t\in T} N_t$ (11)

4.Min Construction Cost: $\min \sum_{t\in T} N_t * Price(L_t)$ (12)

5.Min Transportation distance within the building:

$$\min \sum_{t\in T}(\sqrt{(2h_0 + 2w_0)^2 + {l_0}^2}(L_t - 1) + max\,(H_t, W_t)) \times 2N_t \quad (13)$$

## 3. Case Study

The application of the prototype is illustrated in the following via a comparative case study of a multi-story warehouse project located in the Yantian Port (Figure 2a), the eastern part of central Shenzhen, China.

The current general layout (Figure 2b) features two five-story warehouses positioned on the southeast side of the site. By re-designing and optimizing the general layout with the proposed prototype, the existing project is used as a benchmark for evaluating the efficacy of the design approach.

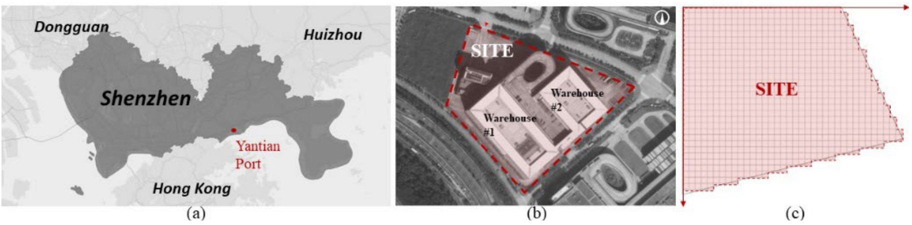


*Figure 2. Site location (a), current general layout (b), and gridification of the site(c)*

### 3.1. PRELIMINARY DEFINITION

After gridifying of the site (Figure 2c), we defined fundamental assumptions related to WTs, WFCs, and RUs. 1) They are all rectangular, with the wall width being negligible. 2) A WFC adhering to fire safety regulations consists of 25 grid cells. 3) A WT consists of at least two WFCs, at most four WFCs, and one RU. WTs can be arranged with a 0-

degree orientation or rotated by 90 degrees, resulting in a set of 6 possible configurations, denoted as $T = \{t_1, t_2, t_3, t_4, t_5, t_6\}$. 4) The prescribed spacing between WTs is one grid and is contained in the templates. An illustrative diagram based on the assumptions is shown in Figure 3.

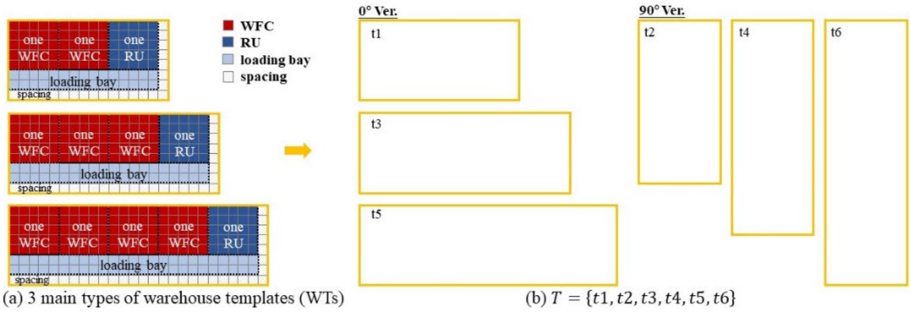


*Figure 3. Preliminary definition of templates*

The area of the site is approximately 55,000 ㎡. Considering the local regulations on floor area ratio (3.0) and building height (50m), as well as the practical requirements of decision-makers for this real-world project, we have calculated that the total number of WFCs placed on the site should not exceed 40, with a maximum number of building storeys $L_0 = 6$. The fixed reference point representing the site entrance is defined as $(24, 20)$. Additionally, based on the given construction cost data, we have compiled a rough cost estimate, as shown in Table 1.

Table 1. Given average construction cost (CNY)

| Storeys / WT | Per ㎡ | t1, t2 | t3, t4 | t5, t6 |
|---|---|---|---|---|
| [redacted] | 2,200 | 33,264,000 | 44,352,000 | 55,440,000 |
| | 2,800 | 84,672,000 | 112,896,000 | 141,120,000 |
| | 3,200 | 217,728,000 | 290,304,000 | 362,880,000 |
| | 3,600 | 302,400,000 | 403,200,000 | 504,000,000 |
| | 4,000 | 399,168,000 | 532,224,000 | 665,280,000 |
| | 4,400 | 217,728,000 | 290,304,000 | 362,880,000 |

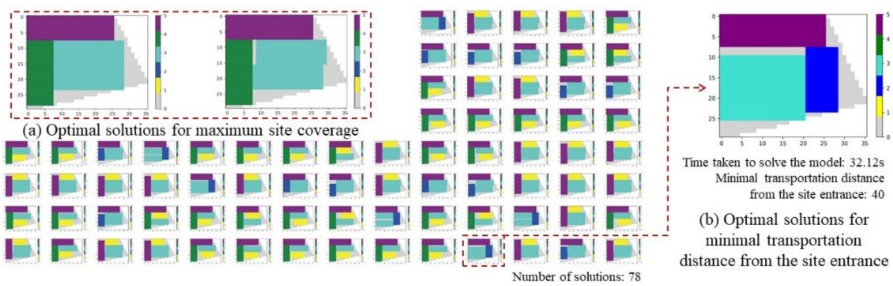


*Figure 4. Optimal solutions generated through IP*

## 3.2. ALTERNATIVE GENERAL LAYOUT GENERATION

This section demonstrates a set of optimal solutions generated through IP for maximum site coverage (Figure 4a) and minimal transportation distance from the site entrance (Figure 4b). Each of these solutions serves as an alternative proposal for the existing general layout.

## 3.3. OPTIMIZATION RESULTS

NSGA-II is applied here to solve the multi-objective problems. The numbers of initial individuals and generations are both set to be 100. The Pareto Fronts obtained are visualized in a three-dimensional chart. A comparative analysis of two sets of solutions is conducted and further explained as follows.

### *3.3.1. Optimal Solutions for Land Intensification*

In this section, we fix the value of diversity at 3 or 4 and use it as a constraint, with land intensification as the variable. The obtained Pareto Fronts (Figure 5) spans from the top-left to the bottom-right of the plot, which illustrates the gradual change of layout from “density and intensification” to “low cost and transportation”.

In the analysis, a total of five solutions grouped into three sets were examined, focusing on better intensification. The comparison involved cost, total number, and transportation metrics. Set 1 exhibited the highest intensification but the lowest WFC quantity. Between Set 2 and Set 3, Set 2 outperformed in both intensification and total numbers, while Set 3 was less intensive but more cost-effective. Notably, Solution 1(a) and Solution 3(c) share the same configuration in the previous IP results, as do Solution 2(b) and Solution 3(d). A closer look at the original configurations revealed better transportation in the former one. Thus, for those pursuing the shortest transportation distance, the former layout configuration is recommended, while those emphasizing WFC total number and intensification may prefer the latter.

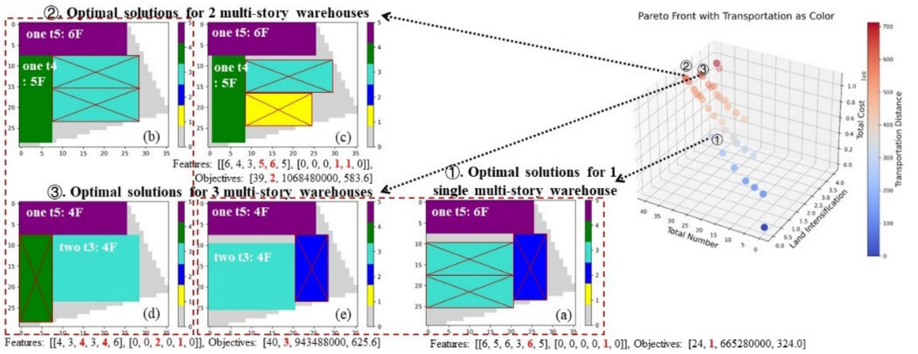


*Figure 5. Optimal solutions for land intensification*

### *3.3.2. Optimal Solutions for Diversity*

In this section, we set diversity as the variable, with the value of intensification fixed at 4 and treated as a constraint. This approach enables us to derive solutions for different levels of diversity. As shown in Figure 6, the majority of the solutions are clustered towards the middle of the "Total Number" and "Land Intensification" range, with a moderate "Total Cost" and "Transportation Distance", representing a balanced trade-off among the considered objectives.

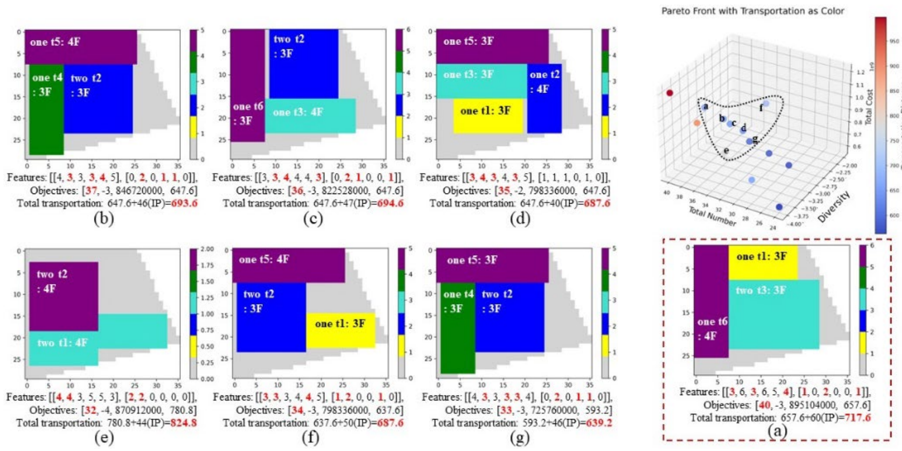


*Figure 6. Optimal solutions for diversity*

In the analysis, 7 solutions are selected from the cluster with costs under 1,000,000,000, transportation under 800, and a total number greater than or equal to 32. Notably, Solution (a) stands out from a long-term sustainability perspective due to its highest number of WFCs. This result is consistent with the objective of maximizing site coverage, confirming alignment between the outcomes of IP and NSGA-II.

## 4. Conclusion

This research proposed a generation and optimization prototype model that supports the multi-story logistics warehouse general layout design. The prototype exhibits a significant advantage in providing considerable decision-making flexibility for navigating trade-offs between efficiency and sustainability. The future refinement of the model will involve rotations of the grid, particularly in sites with non-orthogonal contours. Additionally, enhancing the diversity of warehouse templates (WTs) will be considered, taking into account practical scenarios such as two warehouses sharing a circular ramp. While the prototype is developed using Shenzhen as a sample, its potential applicability extends to other densely populated or concentrated metropolitan areas confronted with comparable challenges of land scarcity and intensive development, which requires further research.

## References

Aderneck, E. (2020). From Horizontal to Vertical: Industrial Intensification Grows Up. *Development*, *Volumn 51, No.1*(Spring 2020), 74.

Buldeo Rai, H., Kang, S., Sakai, T., Tejada, C., Yuan, Q. (Jack), Conway, A., & Dablanc, L. (2022). 'Proximity logistics': Characterizing the development of logistics facilities in dense, mixed-use urban areas around the world. *Transportation Research Part A: Policy and Practice*, *166*, 41–61. https://doi.org/10.1016/j.tra.2022.10.007

Coello Coello, C. A. (2006). Evolutionary multi-objective optimization: A historical view of the field. *IEEE Computational Intelligence Magazine*, *1*(1), 28–36. https://doi.org/10.1109/MCI.2006.1597059

Colicchia, C., Marchet, G., Melacini, M., & Perotti, S. (2013). Building environmental sustainability: Empirical evidence from Logistics Service Providers. *Journal of Cleaner Production*, *59*, 197–209. https://doi.org/10.1016/j.jclepro.2013.06.057

Giuliano, G., & Kang, S. (2018). Spatial dynamics of the logistics industry: Evidence from California. *Journal of Transport Geography*, *66*, 248–258. https://doi.org/10.1016/j.jtrangeo.2017.11.013

Heitz, A., Dablanc, L., Olsson, J., Sanchez-Diaz, I., & Woxenius, J. (2020). Spatial patterns of logistics facilities in Gothenburg, Sweden. *Journal of Transport Geography*, *88*, 102191. https://doi.org/10.1016/j.jtrangeo.2018.03.005

Hua, H., Hovestadt, L., Tang, P., & Li, B. (2019). Integer programming for urban design. *European Journal of Operational Research*, *274*(3), 1125–1137. https://doi.org/10.1016/j.ejor.2018.10.055

Keatruangkamala, K., & Sinapiromsaran, K. (2005). Optimizing Architectural Layout Design via Mixed Integer Programming. In B. Martens & A. Brown (Eds.), *Computer Aided Architectural Design Futures 2005* (pp. 175–184). Springer Netherlands. https://doi.org/10.1007/1-4020-3698-1_16

Lim, H., & Park, M. (2020). Modeling the Spatial Dimensions of Warehouse Rent Determinants: A Case Study of Seoul Metropolitan Area, South Korea. *Sustainability*, *12*(1), Article 1. https://doi.org/10.3390/su12010259

Lv, H., & Wang, T.-K. (2020). Development of a Nonlinear Integer Optimization Model for Tenant Mix Layout in a Shopping Centre. *Advances in Civil Engineering*, *2020*, e2787351. https://doi.org/10.1155/2020/2787351

Ploos van Amstel, W., Balm, S., Tamis, M., Dieker, M., Smit, M., Nijhuis, W., & Englebert, T. (2021). *Go electric: Zero-emission service logistics in cities*. Hogeschool van Amsterdam.

Sakai, T., Kawamura, K., & Hyodo, T. (2015). Locational dynamics of logistics facilities: Evidence from Tokyo. *Journal of Transport Geography*, *46*, 10–19. https://doi.org/10.1016/j.jtrangeo.2015.05.003

Wang, R., Wang, Y., Gundersen, T., Wu, Y., Feng, X., & Liu, M. (2021). A multi-objective optimization method for industrial park layout design: The trade-off between economy and safety. *Chemical Engineering Science*, *235*, 116471. https://doi.org/10.1016/j.ces.2021.116471

Wu, Z., Ran, K., Lv, H., & Wang, T.-K. (2023). Generative design: Integrating rent and retail compatibility goals for automated tenant mix layout. *Journal of Building Engineering*, *79*, 107845. https://doi.org/10.1016/j.jobe.2023.107845

Xiao, Z., Yuan, Q., Sun, Y., & Sun, X. (2021). New paradigm of logistics space reorganization: E-commerce, land use, and supply chain management. *Transportation Research Interdisciplinary Perspectives*, *9*, 100300. https://doi.org/10.1016/j.trip.2021.100300

Yuan, Q., & Zhu, J. (2019). Logistics sprawl in Chinese metropolises: Evidence from Wuhan. *Journal of Transport Geography*, *74*, 242–252. https://doi.org/10.1016/j.jtrangeo.2018.11.019

Zhang, G. Q., & Lai, K. K. (2006). Combining path relinking and genetic algorithms for the multiple-level warehouse layout problem. *European Journal of Operational Research*, *169*(2), 413–425. https://doi.org/10.1016/j.ejor.2004.08.007

Zhang, G. Q., Xue, J., & Lai, K. K. (2002). A class of genetic algorithms for multiple-level warehouse layout problems. *International Journal of Production Research*, *40*(3), 731–744. https://doi.org/10.1080/00207540110093909