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# Research on Multi-Objective Optimization of Renovation Projects in Old Residential Areas Based on Evolutionary Algorithms

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**Abstract:** Old residential areas present unique challenges in terms of design, stakeholders, and renovation requirements compared to traditional building projects. However, unreasonable construction plans can lead to delays, cost overruns, poor quality, and conflicts between the construction party and local residents. This article proposes an optimization model that prioritizes progress, quality, and cost as the key control objectives, leveraging the actual conditions of renovating old residential areas. The NSGA-II genetic algorithm is employed to solve the mathematical model. To validate the effectiveness and scientific rigor of the algorithm, a renovation project in an old residential area in Wuhan is used as a case study. The findings of this study offer valuable theoretical support for decision makers in selecting appropriate construction plans.

**Keywords:** old residential areas; construction renovation; network planning technology; multi-objective optimization; NSGA-II genetic algorithm

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## 1. Introduction

With the rapid growth of China's real estate industry over the past 20 years, the average per capita living area in Chinese households has surpassed 41.76 square meters, approaching levels seen in developed economies. The current housing market has transitioned from incremental growth to a focus on existing stock. According to the 2023 National Real Estate Market Basic Situation Survey Report by the National Bureau of Statistics, China's real estate development investment in 2023 amounted to CNY 11,091.3 billion, which represents a 9.6% decrease compared to the previous year [1]. This decline can be attributed to various factors, such as negative population growth and economic downturn pressures. As a result, there has been a significant shift in people's housing demands. Houses are no longer solely valued for their residential attributes but are also assessed based on various dimensions, including spatial comfort, environmental friendliness, community services, and the availability of comprehensive commercial facilities in the surrounding areas [2].

In first- and second-tier cities, there exists a challenge stemming from a shortage of new housing options, limited land resources, and the high cost of demolition. As a result, addressing this predicament requires a focus on renovating old residential areas. This approach entails enhancing the residential environment, improving infrastructure functions, enhancing building performance, establishing smart and secure communities, and implementing efficient property management mechanisms. These measures represent effective strategies for resolving the aforementioned contradiction and meeting the housing needs of urban populations in a sustainable manner [3].

According to data from the Ministry of Housing and Urban Rural Development, China has nearly 170,000 old residential areas, encompassing more than 42 million households and a total building area of approximately 4 billion square meters. Given the vast scale of these areas, renovating them presents numerous challenges. Unforeseen factors, such as the absence of construction drawings for existing buildings, difficulties in conducting household surveys, and challenges in deploying construction machinery, often arise during the renovation process. Undoubtedly, such factors pose significant challenges for project managers overseeing renovation projects in old residential areas. Ensuring effective control over the progress and cost of these projects while meeting quality objectives is a vital concern for construction managers. Addressing this concern requires careful planning, coordination, and the implementation of appropriate strategies throughout the renovation process.

Many scholars have conducted extensive research in the field of renovation of old residential areas. Lihtmaa and Kalamees [4] focused on the renovation strategies and technical solutions for large-scale residential construction in post-World War II Europe. Their research aimed to evaluate the implementation plans of mass-renovation approaches by EU member states and identify the main barriers to their adoption. Shach-Pinsly [5] explored the impact of multi-parameter decision making on urban renewal using the TAMA38 project in Haifa City as a case study. The research underscored the importance of tailoring urban renewal strategies to specific locations and emphasized the responsibility of authorities in planning open public spaces throughout the process. In terms of technical research, Shen et al. [6] utilized an experience-based mining method to extract practical knowledge from previous urban renewal projects. This knowledge aimed to support the participation of multiple stakeholders in decision-making processes related to Chinese urban renewal. Lekan et al. [7] focused on introducing systematic data for urban housing construction, renewal, and upgrading. Through a stratified survey method, they identified key factors influencing urban housing renewal and upgrading. Zhou et al. [8] also adopted an experience-based mining method to extract practical experiences from previous urban renewal projects. Their research aimed to support decision-making processes in urban renewal involving multiple stakeholders. In terms of evaluation research related to the renovation of old residential areas, Zhu et al. [9] developed a framework for assessing the relative performance of multiple neighborhood renewal projects using a hybrid AHP-TOPSIS method. Huo et al. [10] constructed a list of risk factors for retrofit projects in old residential areas. Through a questionnaire survey, they collected opinions from participants regarding the possibility and impact of these risk factors. They developed a risk assessment model based on C-OWA and grey cluster analysis to evaluate risk levels and proposed risk management and control measures accordingly.

Research on the renovation of old residential areas with a focus on carbon emission reduction has garnered significant attention in recent years. Luo et al. [11] conducted a life cycle assessment to analyze the impact of carbon emissions during the renovation process of old residential areas. Their study comprehensively considered carbon emissions at various stages, including materialization, demolition, and use. He et al. [12] established carbon emission values for retrofitting buildings and proposed a method for calculating carbon accounting. Additionally, they introduced carbon emission evaluation indexes from an economic perspective, such as carbon increments, carbon emission intensity, carbon savings during the operation phase, and the static payback period of carbon increments. Furthermore, Feng et al. [13] employed a scenario-based analysis to evaluate the life cycle of greenhouse gas (GHG) emissions of six different renovation and reconstruction scenarios. They calculated the total life cycle emissions for each scenario, considering embodied and operational emissions, as well as emissions from building construction and maintenance. Notably, the researchers utilized a combined approach of Building Information Modeling–Life Cycle Assessment (BIM-LCA) using SimaPro software (V7.1.8) to assess the embodied GHG emissions. The outcomes of the study can support city planners and urban development planners in making informed decisions regarding the development of aging building stock, particularly in high-population-density neighborhoods.

Based on the studies mentioned, it is evident that current research on renovation projects for old residential areas primarily focuses on renovation methods, strategies, and evaluations of projects. However, there seems to be a lack of research conducted by scholars specifically addressing the multi-objective optimization problem during the renovation construction process in old residential areas.

The application of multi-objective optimization research schemes utilizing various algorithms has been widely adopted in different engineering fields. Ning et al. [14] analyzed the reduction of noise pollution for workers by optimizing construction site layout planning during the preconstruction stage. They aimed to strike a balance between noise reduction, safety improvement, and cost control, considering the potential trade-offs between these objectives. Anvari et al. [15] introduced genetic algorithms for optimizing the manufacturing, transportation, and assembly processes of prefabricated components. Their objective was to maximize safety while minimizing time and cost. Tran et al. [16] proposed a novel multiple objective symbiotic organisms search (MOSOS) algorithm to address safety risks arising from unreasonable work scheduling during the construction process. Li et al. [17] conducted sensitivity analysis using machine learning techniques, such as Random Forest Regressor (RFR), Gradient Boosting Regressor (GBR), and Decision Tree Regressor (DTR), to explore the relationship between design variables and environmental objectives. Their research aimed at providing a scientific foundation for energy saving, emission reduction, and decision-making approaches in the development of old communities.

Indeed, there are several research methods available for tackling multi-objective optimization problems. Jun and El-Rayes [18] introduced a multi-objective optimization model specifically designed for scheduling multiple labor shifts in construction projects. Alsayegh and Hariga [19] proposed hybrid meta-heuristic methods to solve the multi-resource leveling problem, incorporating activity splitting techniques. Cheng et al. [20] applied a serial method to consider individual user priorities when determining the active time and project duration. They further integrated Fuzzy Clustering Chaotic-based Differential Evolution (FCDE) and the serial method to create a novel optimization model called the FCDE-RCPSP (Fuzzy Clustering Chaotic-based Differential Evolution for Solving Resource Constrained Project Scheduling Problem). Tran and Hoang [21] proposed a novel approach for resource leveling called Resource Leveling based on Differential Evolution (RLDE).

Based on the literature reviewed, it appears that the genetic algorithm (GA) is a commonly utilized method for solving multi-objective optimization problems. Chen and Weng [22] developed a two-phase GA model that considers both time–cost trade-offs and resource scheduling effects within the construction project. Liu and Zhang [23] introduced an improved genetic algorithm to tackle the objectives in construction projects. Immanuel [24] introduced the principle and implementation path of the GA algorithm comprehensively. Gang [25] analyzed the performance of the GA algorithm.

In addition, there are some other classic optimization algorithms, including, for example, sailed fish optimizer algorithms (SFOs), particle swarm optimization algorithms (PSOs), and the whale optimization algorithm (WOA). These multi-objective algorithms are quite common and have been studied by many scholars.

Shadravan et al. [26] studied the solution method of the SFO algorithm in engineering optimization problems systematically. Shami et al. [27] provided a comprehensive overview of the PSO algorithm. Gharehchopogh and Gholizadeh [28] provided an overview of the WOA algorithm to solve optimization problems in various categories.

Based on the above literature review, we know that genetic algorithms have strong global search ability and good robustness, making parallel processing simple and easy to implement. They can easily adapt algorithms to different application requirements. On the other hand, given the limited sample size and the limited search space in this study, the GA algorithm has obvious advantages compared to other algorithms. So, we chose the GA algorithm to achieve a multi-objective solution.

Furthermore, the non-domination-based genetic algorithm (NSGA-II) stands out as a popular algorithm in the realm of genetic algorithms. NSGA-II offers distinct advantages in terms of computational speed and robustness while maintaining a uniformly distributed set of non-inferior optimal solutions. Alothaimeen et al. [29] proposed NSGA-II as a multi-objective optimization tool to determine the optimal solution, considering life cycle cost and sustainability measures for a new construction project. For the multi-objective optimization problem of shield construction parameters, Wu et al. [30] introduced a hybrid intelligence framework that combines the random forest (RF) algorithm with NSGA-II. This framework effectively addresses the limitations of time-consuming and costly establishment and verification procedures associated with traditional prediction models. Ghoddousi et al. [31] presented a multi-mode resource-constrained discrete time–cost–resource optimization model. They utilize NSGA-II to search for non-dominated solutions considering total project time, cost, and resource moment deviation as the three objectives. Their model assists in selecting the starting time and execution mode of each activity, while adhering to all project constraints.

In summary, we can derive the following key points. Firstly, the renovation of old residential areas has garnered significant research attention in recent years. However, there remains a lack of comprehensive research on the refined construction management aspects of such projects. Secondly, the challenge of refined management can be addressed through multi-objective optimization of the renovation project. Lastly, there exist diverse methods for tackling multi-objective optimization problems. Given the advantageous iterative nature of genetic algorithms, we have selected this approach to solve the multi-objective optimization problem of construction management for renovation projects in old residential areas.

## 2. Models and Methods

### *2.1. Construction Phase Multi-Objective Model Construction*

#### 2.1.1. Multi-Objective Factor Analysis

The management of renovation projects in old residential areas shares similarities with general project construction management, where quality, cost, and time form a stable triangular relationship, as depicted in Figure 1. Changes in one management element can affect the others, and the impact of project plan adjustments on related factors can vary across different projects. For instance, enhancing quality may increase the overall project cost or reduce costs through improved management measures. In the study of cost control, if there is a potential project budget overrun, it becomes necessary to adjust the project work plan to achieve comprehensive project control. In this process, the weights assigned to time, cost, and quality should be determined based on the unique characteristics of the project, and key adjustments should be focused on elements with higher weights. In the case of renovation projects in old residential areas, which are typically government-led initiatives, the primary objective is to improve the quality of existing buildings and enhance the living standards of residents. Therefore, within the three main factors of time, cost, and quality mentioned earlier, optimizing engineering quality objectives should take precedence. This article's research approach aims to optimize both time and cost goals while ensuring that engineering quality meets the required standards.

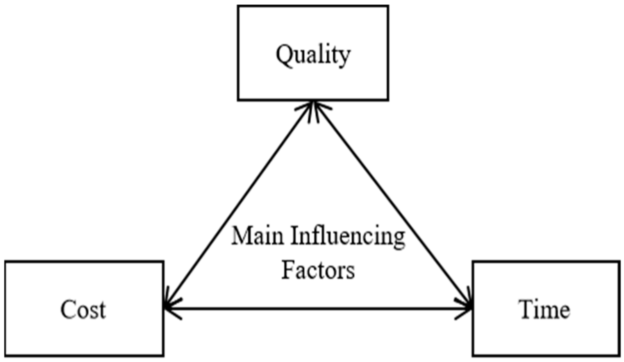


**Figure 1.** The relationship between construction time, quality, and cost.

2.1.2. Mathematical model establishment

The multi-objective optimization problem addressed in this study focuses on the renovation of old residential areas, aiming to achieve the shortest construction period, the lowest cost, and the highest quality level. Various constraints are considered, such as the total project duration, the overall cost, logical relationships in the network diagram, and the work execution mode. Given the interplay between time, cost, and quality, the optimization problem for renovating old residential areas can be summarized as follows.

(I) Objective function

$$\min T = \max TF_i \tag{1}$$

$$\min C = \sum_{i=1}^{n} [C_i^r + \lambda_i (T_i - T_i^r)^2] + \beta T - \gamma (T_{con} - T) \tag{2}$$

$$\lambda_i = \frac{C_i^{\max} - C_i^r}{T_i^r - \frac{T_i^{\max} - T_i^{\min}}{2}} \tag{3}$$

$$\max Q = \prod_{i=1}^{n} R_{Qi} \left[ 1 - \prod_{j=1}^{m} (1 - R_{Qj}) \right] \tag{4}$$

The objective function (1) aims to minimize the duration, which is the maximum completion time ($\max TF_i$) among all tasks. The objective function (2) aims to minimize the demand cost ($\min C$), where $C_i^r$ represents the direct cost during normal working hours of work $i$, $T_i$ represents the actual duration of work $i$, $T_i^r$ represents the normal duration of work $i$, $\beta$ represents the project's indirect cost coefficient, $\gamma$ represents the project's reward and punishment coefficient, and $T$ represents the project's optimization time. Additionally, $T_{con}$ represents project's contract duration, and $\lambda_i$ is the boundary-cost-increasing parameter calculated as shown in Equation (3), where $C_i^{\max}$ represents the maximum direct cost of work $i$, $T_i^{\min}$ represents the shortest duration of work $i$, and $T_i^{\max}$ represents the longest duration of work $i$. The objective function (4) reflects seeking a correlation between maximizing the quality value and the level of work quality. Among them, $Q$ represents the overall quality level of the project, and $R_{Qi}$ represents the quality level of the preceding work for each process.

(II) Constraint condition

$$T_i^{\min} \le T_i \le T_i^{\max} \tag{5}$$

$$Q_i^{\min} \le Q_i \le 1 \tag{6}$$

$$\max\{TF_h\} \leq TS_i \tag{7}$$

$$T \leq T_{\text{con}} \tag{8}$$

$$C \leq C_{\text{con}} \tag{9}$$

$$Q_{\text{min}} \leq Q \leq 1 \tag{10}$$

Formula (5) represents the constraint on the duration of work. Work i can be adjusted within the longest and shortest duration. Formula (6) represents the constraint of the quality level, and work i must meet the constraint of the lowest quality level ($Q_i^{\text{min}}$). Formula (7) represents the constraint of the tight preceding relationship, which must be completed before work i can proceed. Formula (8) represents the constraint of the contract duration, and the optimized duration cannot exceed the contracted duration ($T_{\text{con}}$). Formula (9) represents the constraint of contract cost, and the adjustment of cost cannot exceed the agreed-upon price in the contract ($C_{\text{con}}$). Formula (10) represents the constraint of the project quality level, and the overall quality level of the project cannot be lower than the minimum quality value ($Q_{\text{min}}$).

### *2.2. Solving Multi-Objective Optimization Problems Based on the Evolutionary Algorithm*

#### 2.2.1. Application of the NSGA-II Algorithm

The Multi-Objective Optimization Evolutionary Algorithm (MOEA) incorporates evolutionary algorithms to address multi-objective optimization challenges. Common MOEAs include Non-Dominated Sorting Genetic Algorithms (NSGAs) and NSGA-II. This study utilizes the NSGA-II algorithm to solve multi-objective optimization problems in renovating old residential areas. The cloud computing process depicted in Figure 2 involves several main steps:

(I) Parameter settings: Set the population size to N, the number of iterations to M, and the crossover probability and mutation probability to $P_c$ and $P_m$, respectively.
(II) Population initialization: Generate the initial population based on the coding scheme and assign initial gene values.
(III) Fitness evaluation: First, the duration, cost, and quality target values for each individual in the current population are calculated. Then, non-dominated sorting is performed on the population's individuals to form different levels, and the crowding distance is calculated for individuals at the same level. Finally, all individuals in the population are sorted.
(IV) Perform evolutionary operations: Perform selection, crossover, and mutation operations on contemporary population F to generate a new population S.
(V) Elitism reserved strategy: Mix the parent population F and the offspring population S, and reallocate the fitness. Individuals with larger crowding distances are selected from lower levels to enter the next-generation population, forming a new population S* with a size of N.
(VI) Termination judgment: Return to step four and continue to the next iteration. Cease the operation once the maximum number of iterations has been reached, and produce the optimal solution.

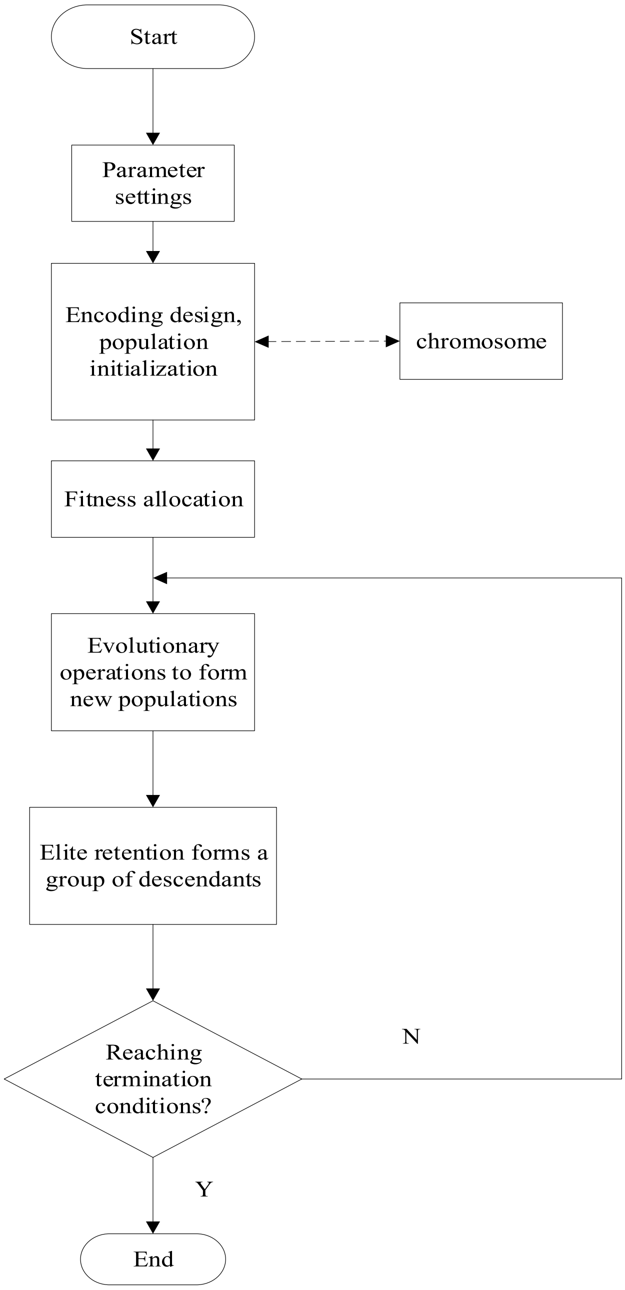


**Figure 2.** Flowchart of multi-objective optimization solution based on evolutionary algorithm.

### 2.2.2. Algorithm Encoding and Initialization

Before running the algorithm, it is necessary to set the basic parameters, including the population size (N), number of iterations (M), the crossover probability ($P_c$), and the mutation probability ($P_m$). In order to solve the multi-objective optimization problem related to the project time, cost, and quality in the renovation of old residential areas, this study adopts a double-layer coding method using a work list and a work mode. This encoding method represents individuals as a work list that includes tight antecedent constraints and a corresponding list of work patterns for each job. Figure 3 illustrates the coding diagram for this approach.

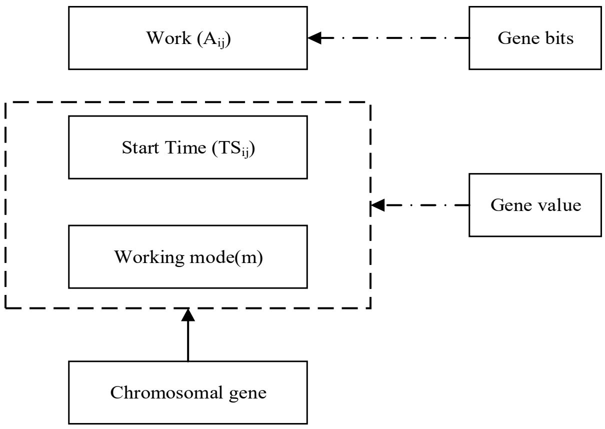


**Figure 3.** Gene coding schematic diagram.

The work list encoding method represents individuals as a work list that adheres to strict preceding relationships, as determined by the logical connections in the network diagram. Each work denoted as $A_{ij}$, must be scheduled after all of the tasks within its immediate work set $\{P_{hi}\}$, ensuring that the start times of each project are sequenced chronologically from the front to the back.

2.2.3. Virtual Fitness Allocation

The individual's fitness is determined based on the hierarchy of multiple objective values and the crowding distance. According to the non-dominated relationships between individuals, the population is divided into different non-dominated levels, and individuals on the same level represent the density of their location through crowding distance.

(I) Non-dominated sorting

Divide individuals in contemporary populations into different levels based on non-dominated relationships in a multi-objective space, where the first level represents the optimal solution set of the population, and subsequent levels correspond to the optimal solution sets after removing the upper level.

First, sequentially select all individuals in the population and calculate the number of individuals that dominate each individual. If an individual is not dominated by any other individuals, it is moved to the current level. Exclude individuals at the current level, recalculate the remaining individuals, and move those that satisfy non-dominant relationships to the next level. Repeat this process of calculating dominance relationships and hierarchical transfer operations until all individuals have completed hierarchical operations within different levels.

(II) Crowding distance

After partitioning the population into non-dominated levels, individuals within the same level do not exhibit dominance relationships, and it is essential to assess the density of positions among individuals at the same level. In order to maintain population diversity and prevent local convergence of the algorithm, priority will be given to ensuring that individuals with larger crowding distances are selected for participation in the evolutionary operation of the next generation.

The crowding distance of an individual in the target space is calculated as the sum of their normalized single-target crowding distances. Taking cost as an example, individuals at a certain level are sorted by cost size, and the middle individual's crowding distance is determined by the normalized difference between the two adjacent individuals' cost objective functions divided by the cost objective range value on that level. The overall crowding distance of an individual in the target space is obtained by aggregating their single objective crowding distances on each objective function using a specific formula.

$$D = \sum_{n=1}^{N} \frac{f_{n,i+1} - f_{n,i-1}}{f_{n,\max} - f_{n,\min}} \tag{11}$$

In the above equation, $N$ represents the number of optimization objectives in multi-objective optimization problems, $f_{n,i-1}$ represents the value of the nth objective function of the preceding individual $i$, $f_{n,i+1}$ represents the value of the nth objective function of the preceding individual $i$, $f_{n,\min}$ represents the minimum value of individuals on this level on the nth objective function, and $f_{n,\max}$ represents the maximum value of individuals on this level on the nth objective function.

2.2.4. Evolutionary Operation

The genetic algorithm's evolutionary process consists of selection, crossover, mutation, and elite preservation strategies. A comprehensive explanation of each step is provided in the following text.

(I) Selection

The selection operation is the most important step in genetic algorithms, which determines whether the genetic information of excellent individuals can be transmitted to the next generation. In a multidimensional, objective space, the distance between two feasible solutions a and b is defined by the standard distance on each objective function.

$$d = \sqrt{\left|(f_{1,a} - f_{1,b})/f_{1,b}\right|^2 + \left|(f_{2,a} - f_{2,b})/f_{2,b}\right|^2 + \ldots\ldots + \left|(f_{n,a} - f_{n,b})/f_{n,b}\right|^2} \tag{12}$$

Individuals with large crowding distances from non-dominated solutions in contemporary populations are selected as parents X to maintain population diversity. The individual closest to X in the target space is then selected as parent Y.

(II) Crossover

By utilizing the single point crossover method to conduct crossover operations on individuals with lower fitness within the population, new individuals are generated to replace the original ones. The crossover probability $P_c$ is set to facilitate crossover operations on individuals with lower fitness in the population, assuming that parents intersect at point $q$.

$$\text{Parent individual}: J^f(J_1^f, J_2^f, \ldots, J_q^f, \ldots, J_n^f, m(J_1^f), m(J_2^f), \ldots, m(J_q^f), \ldots, m(J_n^f))$$

$$\text{Maternal individual}: J^m(J_1^m, J_2^m, \ldots, J_q^m, \ldots, J_n^m, m(J_1^m), m(J_2^m), \ldots, m(J_q^m), \ldots, m(J_n^m))$$

$$\text{Offspring individual}: J^s(J_1^s, J_2^s, \ldots, J_q^s, \ldots, J_n^s, m(J_1^s), m(J_2^s), \ldots, m(J_q^s), \ldots, m(J_n^s))$$

In the crossover process of the work list, a random number $q$ is generated, $1 \le q \le n$, where the previous $q$ genes in offspring $J^s$ come from the parent individual, and the $q+1$ to $n$ genes come from the mother individual. Select from the front to back based on the relative position of the genes to be selected in the maternal individual. In the crossover process of work patterns, a new random number $q*$ is generated. The work patterns of the previous $q*$ genes in offspring individual $J^s$ come from the parent individual, while the work patterns of the $q*+1$ to $n$ genes in offspring individual $J^s$ come from the mother individual.

(III) Mutation

This study utilizes the uniform mutation method to conduct mutations while maintaining the logical relationship of work and preserving the work mode. The mutation probability Pm is used to determine whether genes in the work list will undergo mutation. If a randomly generated number is less than the mutation probability during the mutation process, a mutation occurs in the work list. During gene mutation, an insertion point within the immediately preceding and following sets of work is randomly selected for insertion. Additionally, the set mutation probability determines whether genes in the pattern list will undergo mutation. When a gene undergoes mutation, one of the executable modes of the job is chosen to replace the original working mode, along with setting corresponding acceptance rules.

To enhance the search capability of the algorithm, this study took inspiration from the simulated annealing algorithm. Initially, a higher mutation probability is set to increase population diversity during computation. Subsequently, a smaller mutation probability is employed to maintain the search range near the optimal solution in later stages of operation. Based on this approach, we determined the mutation probability for each generation as follows.

$$P_{\mathrm{m}}^{t} = P_{\mathrm{m}} \times \frac{T-t}{T-1} \tag{13}$$

In the formula, $P_{\mathrm{m}}^{t}$ represents the mutation probability of the $t$ generation, $P_{\mathrm{m}}$ represents the initial mutation probability, and $T$ represents the set number of iterations.

(IV) Elite preservation strategies

After conducting evolutionary operations on the parent population F, the offspring population S is generated. In order to preserve exceptional individuals in the population, an elite retention strategy is commonly employed. Initially, the parent and offspring populations are merged to create a population H with a size of 2N. Subsequently, non-dominated hierarchical sorting is performed on the individuals in population H. Through comparison operators, individuals with lower levels and larger crowding distances within the same level are chosen to advance to the next population. Ultimately, a new population S* with a size of N is formed. The specific process is illustrated in Figure 4.

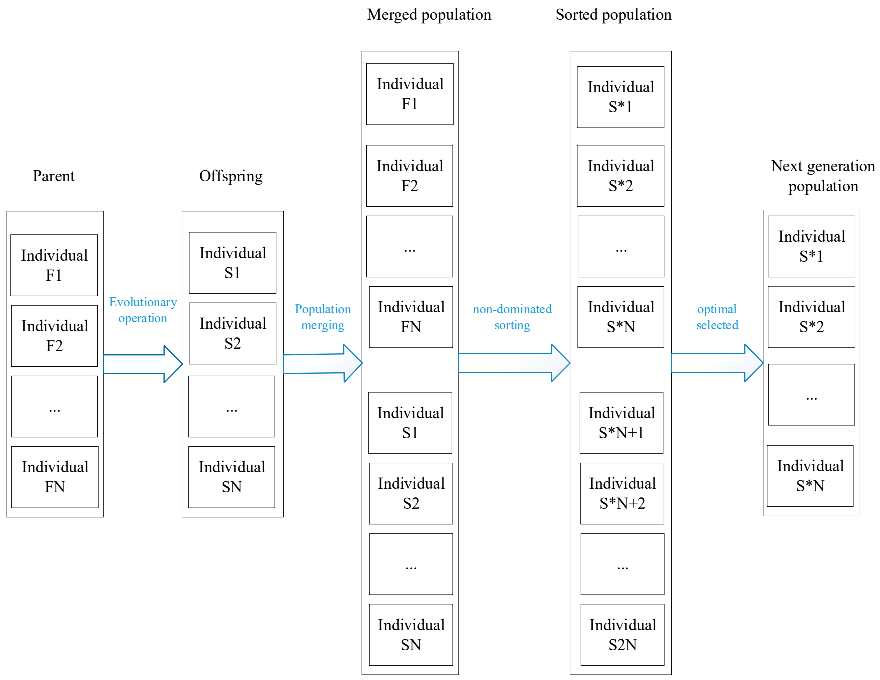


**Figure 4.** Schematic diagram of elite preservation strategy.

## 3. Case Analysis

### *3.1. Project Overview*

This study uses the renovation project of an old residential area in Jianghan District, Wuhan City as a case study to conduct the corresponding research. The realistic view of the project site is shown in Figure 5. The renovation project for this old residential area follows a construction general contracting model and is part of government-led renovation efforts.

The focus of the renovation content is on infrastructure, with basic renovations being the primary focus and upgrade renovations serving as a supplement. The engineering general contracting company is responsible for scientifically managing the progress, cost, quality, and other elements of the old residential areas' renovation project.

**Figure 5.** Realistic view of the project site.

According to the principle of subproject division, the renovation project for old residential areas can be subdivided into 12 subprojects covering various aspects, such as architecture, equipment, transportation, and landscape. The duration of work for each of these 12 subprojects is a variable to be determined. Through on-site research at the renovation site and interviews with the construction general contracting unit, we determined the parameters for the shortest, longest, and normal construction periods for each task, and we established minimum quality requirements. Additionally, based on the previously mentioned model formula relating time, cost, and quality, we determined the normal cost, boundary cost coefficient, and other parameters for each task. The construction network plan and corresponding parameters for the renovation project of old residential areas are presented in Table 1.

Based on the logical relationship of the renovation work in the old residential area project, a dual code network plan is established for each subproject. The network plan can be seen in Figure 6. The dashed arrow in the figure represents the virtual work of the renovation project network plan. It should be emphasized here that virtual work is not a formal task; it only helps to correctly express the relationship between construction work.

**Table 1.** Logic relationships and corresponding parameters of various tasks.

| Work Code | Prior Work | Work Name | Minimum Working Period (Days) | Normal Construction Period (Days) | Longest Construction Period (Days) | Normal Cost (CNY Ten Thousand) | Maximum Cost (CNY Ten Thousand) | Boundary Cost Coefficient | Minimum Quality Requirements |
|---|---|---|---|---|---|---|---|---|---|
| A | \ | Construction of external wall insulation layer | 26 | 28 | 30 | 189 | 192 | 0.06 | 0.90 |
| B | \ | Demolition of external air conditioning units and illegal constructions | 20 | 23 | 26 | 34 | 38 | 0.08 | 0.86 |
| C | A,B | Construction of exterior wall coatings | 6 | 8 | 9 | 82 | 89 | 0.42 | 0.85 |
| D | C | Add security and fire protection facilities | 3 | 4 | 5 | 36 | 39 | 0.34 | 0.83 |
| E | C | Pipeline laying | 10 | 12 | 14 | 200 | 206 | 0.26 | 0.87 |
| F | C | Installation of air conditioning louvers | 7 | 10 | 12 | 23 | 27 | 0.21 | 0.85 |
| G | C | Roof renovation | 25 | 29 | 32 | 66 | 76 | 0.16 | 0.90 |
| H | D,E,F | Road rebuilding | 5 | 8 | 10 | 105 | 110 | 0.33 | 0.85 |
| I | H | Outdoor lighting and landscape construction | 27 | 30 | 34 | 120 | 125 | 0.06 | 0.86 |
| J | I,G | Renovation of parking spaces and addition of car sheds | 3 | 4 | 7 | 9 | 13 | 0.44 | 0.85 |
| K | J | Renovation of building fire exits | 11 | 14 | 15 | 84 | 89 | 0.17 | 0.87 |
| L | K | Restoration and demobilization of construction sites | 2 | 3 | 4 | 18 | 21 | 0.42 | 0.86 |

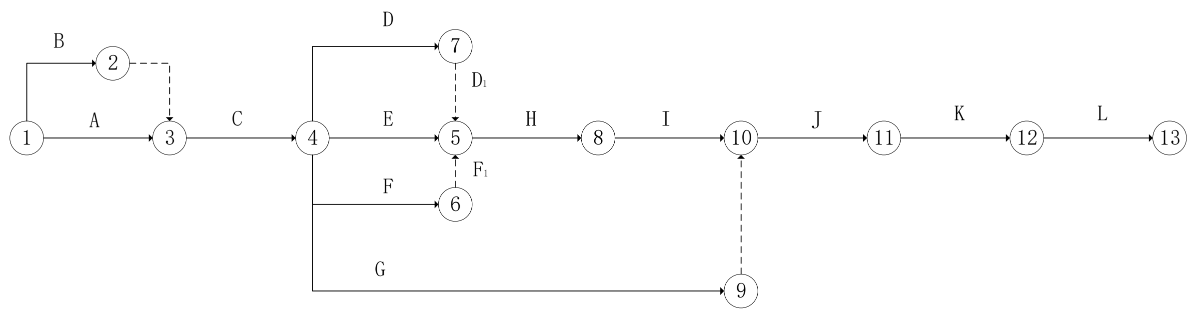


**Figure 6.** Construction network plan for renovation projects.

By adjusting the time parameters of the renovation project, as indicated in Table 2, and considering the construction plan with the shortest duration where the total time difference is 0, it is determined that the key task is A–C–E–H–I–J–K–L. The construction period for this route is 90 days. Similarly, considering the longest construction plan, the key route remains A–C–E–H–I–J–K–L, with a construction period of 123 days. The non-critical tasks are B, D, F, and G. Boundary cost coefficients for each work task can be obtained based on the construction time and cost model.

**Table 2.** Network diagram parameter calculation.

| Work Code | Prior Work | Work Name | Minimum Working Period (Days) | Longest Construction Period (Days) | Minimum Working Period Total Time Difference (Days) | Longest Construction Period Total Time Difference (Days) |
|---|---|---|---|---|---|---|
| A | \ | Construction of external wall insulation layer | 26 | 30 | 0 | 0 |
| B | \ | Demolition of external air conditioning units and illegal constructions | 20 | 26 | 6 | 4 |
| B1 | B | Virtual work 1 | 0 | 0 | 6 | 4 |
| C | A,B | Construction of exterior wall coatings | 6 | 9 | 0 | 0 |
| D | C | Add security and fire protection facilities | 3 | 5 | 7 | 9 |
| D1 | D | Virtual work 2 | 0 | 0 | 7 | 9 |
| E | C | Pipeline laying | 10 | 14 | 0 | 0 |
| F | C | Installation of air conditioning louvers | 7 | 12 | 3 | 2 |
| F1 | F | Virtual work 3 | 0 | 0 | 3 | 2 |
| G | C | Roof renovation | 25 | 32 | 17 | 26 |
| G1 | G | Virtual work 4 | 0 | 0 | 17 | 26 |
| H | D,E,F | Road rebuilding | 5 | 10 | 0 | 0 |
| I | H | Outdoor lighting and landscape construction | 27 | 34 | 0 | 0 |
| J | I,G | Renovation of parking spaces and addition of car sheds | 3 | 7 | 0 | 0 |
| K | J | Renovation of building fire exits | 11 | 15 | 0 | 0 |
| L | K | Restoration and demobilization of construction sites | 2 | 4 | 0 | 0 |

### 3.2. Model Application

Based on the contract, the contracted construction period for this project is 120 days ($T_{con}$= 120), with a contracted project price of CNY 11 million ($C_{con}$= 1100). Additionally, we assume that the overall minimum quality level of the renovation project is 75% ($Q_{min}$ = 0.75). Utilizing objective functions (14)–(16) from the previous text, we have developed a multi-objective optimization model for the time, cost, and quality aspects of the community's renovation phase. And, the meanings of the parameters in the formula have been explained in the previous text.

$$\min T = \max TF_i \tag{14}$$

$$\min C = \sum_{i=1}^{12}\left[C_i^r + \lambda_i (T_i - T_i^r)^2\right] + \beta T - \gamma(120 - T) \tag{15}$$

$$\max Q = \prod_{i=1}^{12} R_{Qi}\left[1 - \prod_{j=1}^{m}(1 - R_{Qj})\right] \tag{16}$$

The constraint conditions are expressed in Formulas (17)–(22). Formula (17) specifies the duration constraint for each work task, indicating that work i must fall within a specified range of durations. Formula (18) represents the quality level constraints for each work, requiring work i to meet a minimum quality level. Formula (19) represents the tight front relationship constraint, allowing work i to proceed only after all preceding tight front work is completed. Formula (20) represents the contract duration constraint, ensuring that the optimized duration does not exceed the contracted duration. Formula (21) represents the contract cost constraint, limiting cost adjustments to stay within the agreed price in the contract. Finally, Formula (22) represents the overall project quality level constraint, ensuring that it does not fall below a minimum value.

$$T_i^{\min} \le T_i \le T_i^{\max} \tag{17}$$

$$Q_i^{\min} \le Q_i \le 1 \tag{18}$$

$$\max\{TF_h\} \le TS_i \tag{19}$$

$$T \le 120 \tag{20}$$

$$C \le 1100 \tag{21}$$

$$0.75 \le Q \le 1 \tag{22}$$

## 4. Results and Discussion

### 4.1. Model Solution

This study utilized MATLAB 2021 software to construct models and solve problems. Firstly, the model parameters were set, with a population size of N = 200, an iteration number of M = 1000, a crossover probability of $P_c = 0.80$, and a mutation probability of $P_m = 0.20$ based on the project's actual situation and the network diagram complexity. Subsequently, the model was solved using the software to obtain 18 non-dominated solutions for the multi-objective optimization model of renovating old residential areas. The non-dominated solution point diagram is depicted in Figure 7.

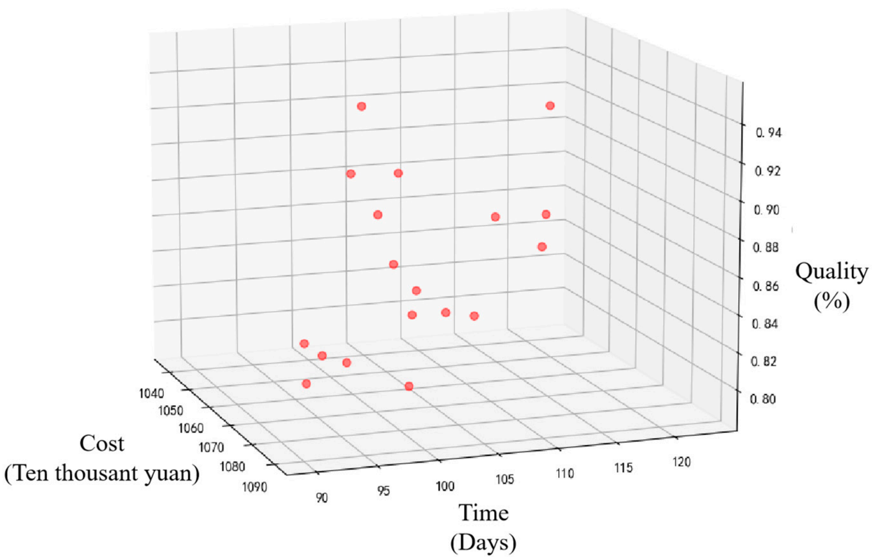


**Figure 7.** 3D scatter plot of time, cost, and quality.

It should be explained that a population is a group composed of several individuals that simulates a biological population. The definition of the number of iterations is the number of times the population stops iterating after satisfying the termination conditions of the genetic algorithm. Cross-probability determines the probability of individual gene exchange in a population. The probability of variation is the probability that an individual's genes undergo mutation.

Running the algorithm yielded 18 non-dominated solutions, each corresponding to a unique construction scheme. The cost, time, and quality level of each construction scheme are detailed in Table 3.

**Table 3.** Cost, time, and quality level of each construction plan.

| Construction Plan | Construction Period (Days) | Cost (CNY Ten Thousand) | Quality Level |
|---|---|---|---|
| 1 | 104 | 1067.38 | 0.84 |
| 2 | 123 | 1036.45 | 0.91 |
| 3 | 112 | 1054.35 | 0.81 |
| 4 | 95 | 1082.66 | 0.82 |
| 5 | 103 | 1070.83 | 0.83 |
| 6 | 101 | 1072.76 | 0.86 |
| 7 | 103 | 1069.42 | 0.79 |
| 8 | 92 | 1087.67 | 0.83 |
| 9 | 123 | 1037.35 | 0.91 |
| 10 | 108 | 1061.02 | 0.82 |
| 11 | 97 | 1079.31 | 0.95 |
| 12 | 90 | 1090.51 | 0.82 |
| 13 | 122 | 1039.23 | 0.85 |
| 14 | 99 | 1076.05 | 0.89 |
| 15 | 115 | 1049.33 | 0.86 |
| 16 | 95 | 1084.65 | 0.92 |
| 17 | 101 | 1074.72 | 0.91 |
| 18 | 90 | 1091.26 | 0.84 |

Among the non-dominated solutions, the optimal solution for each individual objective of project time, cost, and quality is included. Given the actual situation of renovating old residential areas and the decision-making preferences of management personnel, it is essential to provide various construction plans to managers for decision making.

### *4.2. Multi-Objective Decision Making*

Due to the multiple sets of non-dominated solutions generated by the evolutionary algorithms mentioned above, project managers must select a more suitable construction plan based on the specific circumstances. For multi-objective optimization problems, decision schemes for non-dominated solutions consist of two scenarios: the target priority decision and the target weight decision. The first scenario involves prioritizing objectives. For example, in the multi-objective optimization of time, cost, and quality, it may be necessary to prioritize completing the project as early as possible due to specific needs. In this case, progress is the primary objective, followed by cost and then quality. Therefore, the initial focus should be on meeting the requirement for the shortest construction period. Then, the lowest cost requirement is met, and the plan with the best quality is ultimately chosen. The second method involves normalization processing to determine weights based on the importance of each objective, thereby influencing decision making. Normalizing the multi-objective nature of old residential areas allows for setting weights for each objective according to managers' decision-making preferences. After setting the weights, normalized results of time, cost, and quality for each non-dominated solution can be substituted, and a construction plan meeting project managers' decision-making preferences can be selected from multiple groups of construction plans.

Government-led renovation projects in old residential areas prioritize engineering quality as the top concern. Simultaneously, minimizing the renovation period is essential to enhance residential satisfaction and minimize disruption to daily lives. Additionally, while ensuring project quality, government units also aim to minimize project costs. Therefore, the decision-making dimensions for the renovation project of old residential areas are quality as the primary consideration, followed by time and cost. This study utilized genetic algorithm optimization to select 18 construction plans and employed multi-attribute decision making to identify the construction plan with the highest quality level, as presented in Table 4.

**Table 4.** Non-dominated optimization plan for the renovation project of old residential areas.

| Work Code | Duration (Days) | Target Quality | Target Cost (CNY Ten Thousand) | Multi-Objective Optimization Results |
|---|---|---|---|---|
| A | 28 | 0.97 | 209.14 | |
| B | 22 | 0.93 | 51.67 | |
| C | 7 | 0.91 | 87.86 | |
| D | 3 | 0.94 | 37.92 | |
| E | 9 | 0.95 | 30.12 | |
| F | 10 | 0.94 | 206.37 | $T = 97$<br>$C = 1079.31$<br>$Q = 0.95$ |
| G | 28 | 0.96 | 87.67 | |
| H | 6 | 0.93 | 110.43 | |
| I | 28 | 0.92 | 141.89 | |
| J | 3 | 0.93 | 11.01 | |
| K | 12 | 0.93 | 85.21 | |
| L | 3 | 0.96 | 20.02 | |

The optimized construction period of 97 days is 23 days shorter than the contract period, indicating that the genetic algorithm has advanced and expedited the construction schedule. The optimized engineering cost of CNY 10.7931 million represents a savings of CNY 206,900, demonstrating that the optimization results align with cost-planning needs. With a quality level of 0.95, it is evident that the optimized project can maintain overall renovation effectiveness and meet quality requirements.

We have chosen the aforementioned plan as the final construction plan, which will impose higher demands on quality and schedule management of the project. In terms of progress, it is evident that the duration of work D (adding security and fire protection facilities) and J (parking space renovation and shed addition) is three days, necessitating elevated requirements for project progress management.

The project managers of the actual engineering process are required to gather real-time construction information regarding the project and conduct a comparative analysis between the planned and actual values in a timely manner. The implementation of engineering PDCA method is crucial for preventing and correcting the impact on construction progress. Simultaneously, immediate measures should be taken to address any schedule deviations that may arise. Furthermore, a construction information feedback management platform can be established to analyze progress deviations and provide valuable insights for the subsequent development of the project.

For the management of quality, in government-led renovation projects, higher standards are often established for the quality of various forms of renovation work. Therefore, it is essential to rigorously implement process quality control. This includes controlling the quality of process activity conditions and monitoring the input of personnel, materials, machinery, etc. Additionally, it involves controlling the quality of the effectiveness of process activities and inspecting whether the quality standards of each completed work task have been met.

To effectively manage costs and prevent overruns, cost evaluation methods, such as the earned value method, are utilized to comprehensively assess the overall project situation. This involves integrating investment costs with actual project progress to verify the allocation of funds towards project outcomes, while also implementing corrective measures in response to any cost deviations.

## 5. Conclusions

The renovation of old residential areas has emerged as a crucial aspect of China's future urbanization development. However, there are specific challenges associated with government-funded renovation projects in these areas, such as high-quality standards, limited construction space, short construction periods, and complex coordination requirements. These factors significantly increase the difficulty and cost of project management. This study examined the interrelationships between these elements from various perspectives, including project progress, quality, and cost. By utilizing the NSGA-II evolutionary algorithm, a multi-objective genetic algorithm was developed to optimize the renovation projects in old residential areas. By taking a case study of an old residential project in Wuhan, a multi-objective optimization model was established based on time, cost, and quality. The evolutionary algorithms were employed to solve the multi-objective problem. The findings of this research indicate that the genetic algorithm is an effective tool for optimizing the management of renovation projects in old residential areas. Furthermore, specific improvement suggestions for management measures were proposed to project managers based on the optimization results. This study aims to contribute to the development of renovation projects in old residential areas in China. Moreover, it provides valuable insights for project managers, enabling them to adjust management strategies promptly and achieve project management goals more effectively in actual renovation projects.

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## References

1. Chen, Y.; Mo, D.; Tang, S.; Li, H. Measuring real estate policy uncertainty in China. *China Econ. Q. Int.* **2023**, *3*, 23–34. [CrossRef]
2. Zhang, H.; Li, L.; Chen, T.; Li, V. Where will China's real estate market go under the economy's new normal? *Cities* **2016**, *55*, 42–48. [CrossRef]
3. Ding, Q.; Zhang, T.; Zhu, X.; Zhang, J. Impact of Perceived Value and Community Attachment on Smart Renovation Participation Willingness for Sustainable Development of Old Urban Communities in China. *Sustainability* **2022**, *14*, 11675. [CrossRef]
4. Lihtmaa, L.; Kalamees, T. Emerging renovation strategies and technical solutions for mass-construction of residential districts built after World War II in Europe. *Energy Strategy Rev.* **2024**, *51*, 101282. [CrossRef]
5. Shach-Pinsly, D. Three Strategies of Urban Renewal for One National Outline Plan TAMA38: The Impact of Multiparametric Decision-Making on Neighborhood Regeneration. *Architecture* **2022**, *2*, 616–636. [CrossRef]
6. Shen, T.; Yao, X.; Wen, F. The Urban Regeneration Engine Model: An analytical framework and case study of the renewal of old communities. *Land Use Policy* **2021**, *108*, 105571. [CrossRef]
7. Lekan, A.; Faith, O.; Cinwosoko Ninma, A.; Oladipupo Sunday, A. Data on System Approach to Process of urban housing construction, renewal and upgrading. *Data Brief.* **2018**, *19*, 2427–2437. [CrossRef] [PubMed]
8. Zhou, Y.; Lan, F.; Zhou, T. An experience-based mining approach to supporting urban renewal mode decisions under a multi-stakeholder environment in China. *Land Use Policy* **2021**, *106*, 105428. [CrossRef]

9. Zhu, S.; Li, D.; Feng, H.; Gu, T.; Zhu, J. AHP-TOPSIS-based evaluation of the relative performance of multiple neighborhood renewal projects: A case study in Nanjing, China. *Sustainability* **2019**, *11*, 4545. [CrossRef]
10. Huo, X.; Xue, H.; Jiao, L. Risk management of retrofit project in old residential areas under green development. *Energy Build.* **2023**, *279*, 112708. [CrossRef]
11. Luo, X.; Ren, M.; Zhao, J.; Wang, Z.; Ge, J.; Gao, W. Life cycle assessment for carbon emission impact analysis for the renovation of old residential areas. *J. Clean. Prod.* **2022**, *367*, 132930. [CrossRef]
12. He, Y.; Wang, Y.; Song, Z.; Yu, H.; Xue, Y. Study on Carbon Emissions from the Renovation of Old Residential Areas in Cold Regions of China. *Sustainability* **2023**, *15*, 3018. [CrossRef]
13. Feng, H.; Liyanage, D.R.; Karunathilake, H.; Sadiq, R.; Hewage, K. BIM-based life cycle environmental performance assessment of single-family houses: Renovation and reconstruction strategies for aging building stock in British Columbia. *J. Clean. Prod.* **2020**, *250*, 119543. [CrossRef]
14. Ning, X.; Qi, J.; Wu, C.; Wang, W. Reducing noise pollution by planning construction site layout via a multi-objective optimization model. *J. Clean. Prod.* **2019**, *222*, 218–230. [CrossRef]
15. Anvari, B.; Angeloudis, P.; Ochieng, W.Y. A multi-objective GA-based optimisation for holistic Manufacturing, transportation and Assembly of precast construction. *Autom. Constr.* **2016**, *71*, 226–241. [CrossRef]
16. Tran, D.H.; Cheng, M.Y.; Prayogo, D. A novel Multiple Objective Symbiotic Organisms Search (MOSOS) for time-cost-labor utilization tradeoff problem. *Knowl. Based Syst.* **2016**, *94*, 132–145. [CrossRef]
17. Li, Z.; Zou, Y.; Xia, H.; Jin, C. Multi-objective optimization design of residential area based on microenvironment simulation. *J. Clean. Prod.* **2023**, *425*, 138922. [CrossRef]
18. Jun, D.H.; El-Rayes, K. Optimizing the utilization of multiple labor shifts in construction projects. *Autom. Constr.* **2010**, *19*, 109–119. [CrossRef]
19. Alsayegh, H.; Hariga, M. Hybrid meta-heuristic methods for the multi-resource leveling problem with activity splitting. *Autom. Constr.* **2012**, *27*, 89–98. [CrossRef]
20. Cheng, M.Y.; Tran, D.H.; Wu, Y.W. Using a fuzzy clustering chaotic-based differential evolution with serial method to solve resource-constrained project scheduling problems. *Autom. Constr.* **2014**, *37*, 88–97. [CrossRef]
21. Tran, H.-H.; Hoang, N.-D. A Novel Resource-Leveling Approach for Construction Project Based on Differential Evolution. *J. Constr. Eng.* **2014**, *2014*, 1–7. [CrossRef]
22. Chen, P.H.; Weng, H. A two-phase GA model for resource-constrained project scheduling. *Autom. Constr.* **2009**, *18*, 485–498. [CrossRef]
23. Liu, L.; Zhang, C. Research on multi-objective optimization of construction engineering based on improved genetic algorithm. *Procedia Comput. Sci.* **2023**, *228*, 1086–1091. [CrossRef]
24. Immanuel, S.D.; Chakraborty, U.K. Genetic Algorithm: An Approach on Optimization. In Proceedings of the International Conference on Communication and Electronics Systems (ICCES), Coimbatore, India, 17–19 July 2019; pp. 701–708.
25. Gang, L. Genetic Algorithm and Its Application in Software Test Data Generation. In Proceedings of the International Conference on Applied Intelligence and Sustainable Computing (ICAISC), Dharwad, India, 16–17 June 2023.
26. Shadravan, S.; Naji, H.R.; Bardsiri, V.K. The Sailfish Optimizer: A novel nature-inspired metaheuristic algorithm for solving constrained engineering optimization problems. *Eng. Appl. Artif. Intell.* **2019**, *80*, 20–34. [CrossRef]
27. Shami, T.M.; El-Saleh, A.A.; Alswaitti, M.; Al-Tashi, Q.; Summakieh, M.A.; Mirjalili, S. Particle Swarm Optimization: A Comprehensive Survey. *IEEE Access* **2022**, *10*, 10031–10061. [CrossRef]
28. Gharehchopogh, F.S.; Gholizadeh, H. A comprehensive survey: Whale Optimization Algorithm and its applications. *Swarm Evol. Comput.* **2019**, *48*, 1–24. [CrossRef]
29. Alothaimeen, I.; Arditi, D.; Türkakın, O.H. Multi-objective optimization for LEED—New construction using BIM and genetic algorithms. *Autom. Constr.* **2023**, *149*, 104807. [CrossRef]
30. Wu, X.; Wang, L.; Chen, B.; Feng, Z.; Qin, Y.; Liu, Q.; Liu, Y. Multi-objective optimization of shield construction parameters based on random forests and NSGA-II. *Adv. Eng. Inform.* **2022**, *54*, 101751. [CrossRef]
31. Ghoddousi, P.; Eshtehardian, E.; Jooybanpour, S.; Javanmardi, A. Multi-mode resource-constrained discrete time-cost-resource optimization in project scheduling using non-dominated sorting genetic algorithm. *Autom. Constr.* **2013**, *30*, 216–227. [CrossRef]