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Maintenance Decision-Making of an Urban Rail Transit System in a Regionalized Network-Wide Perspective

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Abstract: The networked operation of Urban Rail Transit (URT) brings the new challenge of network-wide maintenance. This research focuses on the URT Network-Wide Maintenance Decision-Making Problem (URT-NMDP), including regionalized maintenance network design and maintenance resource allocation. In this work, we proposed a bi-objective integer programming model that integrates the characteristics of set coverage and P-median models, resulting in the regionalized maintenance network design model. Some critical factors are considered in the model, such as the importance of node, the maximum failure response time, and maintenance guarantee rules. We designed a NSGA-II based algorithm to solve the model. Moreover, due to the uncertainty of failures in the URT network, we developed the method of allocating maintenance resources based on Monte Carlo simulation to strengthen the reliability of the regionalized maintenance network. With the model and algorithm presented in this work, we obtained Pareto optimal solutions of URT-NMDP, i.e., URT network-wide maintenance planning schemes, which include the number and location of maintenance points, the allocation of demand points, and the amount of maintenance units. Finally, a real-world case is studied to evaluate the operating performance of these schemes for verifying the method in our paper. The results of the case study demonstrate that the reasonable and tested-in-practice maximum failure response time is the precondition for the efficient URT maintenance network. The maintenance scheme considered the weighted importance of node shows the optimal performance, with the shortest overall maintenance path and the minimum average failure response time and investment cost on maintenance resources.

Keywords: urban rail transit; regionalized network-wide maintenance; integrated network design model; Monte-Carlo simulation; scenario analysis

1. Introduction

As of the end of 2019, 40 cities in China have opened Urban Rail Transit (URT), and their line length of 6730.27 km and ridership of more than 21.07 billion trips are ranking on the top of the world [1]. High-speed developing URT in construction and operation is stepping into the stage of network-wide maintenance [2]. The high-quality, efficient, and reliable maintenance for URT facilities and equipment is a sufficient guarantee for the active prevention of failures and the safe operation of the URT system [3]. On the one hand, the characteristics of convenience, speed, punctuality, and large-volume for URT increase the attraction rate of public transportation. Car travel is greatly reduced under this situation, which not only relieves traffic congestion, but also reduces traffic pollution (such as noise, carbon emissions, etc.) to maintain the physical and mental health of the people. On the other hand, from a long-term perspective, that is conducive to sustainable development of the URT to explore systematic technology and methods for URT network-wide maintenance. As we all know, the sustainable development of the URT is an important precondition to promote the sustainability of urban transportation and cities. Therefore, more operation and maintenance companies are trying to explore newly network-wide maintenance and management methods, changing from the traditional mode by line into the interconnected network-wide mode. However, the theories and methods oriented around the network-wide maintenance are considerably behind the practice development of URT construction and operation. Thus, quick response, high-efficiency, low-cost, and overall resources are strongly needed for URT network-wide maintenance.

Practically, in cities with the developed URT system in China, such as Beijing, Shanghai, Hongkong, Guangzhou, and Shenzhen, their URT operation companies take the lead in exploring innovative network-wide maintenance mode. For instance, the Shanghai Shentong Metro Group established a comprehensive maintenance center that serves in unified management to maintain the whole network. Its functions include routine inspection, emergency repair, and updates for major equipment in the systems of vehicles, power, communications, and signals [4]. The first trial is usually rooted in the characteristics of the network itself. Guangzhou Metro Group has established a maintenance system with front-end as the core and back-end as the auxiliary since 2013. "The regionalized network-wide maintenance and management mode" is implemented in the front-end, i.e., four maintenance centers are set up to be responsible for the maintenance and repair of equipment and facilities in the whole network. This mode was exactly conducive to the rapid emergency response and efficient resource utilization [5]. Similarly, Hongkong Mass Transit Railway Group applies the network-wide maintenance mode to the general equipment and adopts the professional maintenance method for the driving equipment by line [6]. Additionally, those cities with undeveloped URT system also set a timetable to promote the network-wide maintenance practices, such as the provincial capital, Nanjing, in the middle, and Changchun, Shenyang, and Harbin in the northeast of China.

As Juan F. G. F. and Adolfo C. M. [7] clarified, the maintenance and management of network facilities involves the organization of a large amount of infrastructure, which indeed causes the complexity of maintenance work. It is necessary to comply with integrated procedures, models, decision-making tools, and the technical system to achieve a maintenance level compatible with operations and services. In this sense, although Chinese URT companies continuously promote the innovation of network-wide maintenance modes, the advances still go on slowly, because they are restricted to the differences from cities in the field of URT planning, the distribution of passenger flow, and the technical capacity. Lack of systematic procedure of maintenance for aiding online or offline may result in weakly coordinated organization supporting quick response for a certain service level. Regarding these challenges, the network-wide maintenance and management mode is one of the beneficial development paths to maintain the URT network maintenance at the matched level with its expansion and operation. Therefore, this research focuses on the URT Network-Wide Maintenance Decision-Making Problem (URT-NMDP). Our one work mainly is to explore a novel regionalized URT maintenance network design model and algorithm by balancing the two objections of maintenance efficiency and operating cost while supporting the reliability of resource allocation. The other work is devoted to the decision-making reference by scenario analysis and mode comparison analysis for the unified planning of the service network and coordinated allocation of maintenance resources in those cities with undeveloped UTR systems.

The remainder of this paper is organized as follows. Section 2 reviews related literature on the location-allocation model of network facilities and the method of allocating maintenance resources and shows the paper's contributions. Section 3 describes a novel URT-NMDP and presents a mathematical model and the NSGA-II based algorithm for it. Section 4 demonstrates a real-world case study on the performance of the maintenance schemes to verify the validation of the model and algorithm. Further, the applicability of the mode in this paper is provided by comparing it with other modes, followed by Section 5, where the conclusions and future research recommendations are given.

2. Literature Review

2.1. Multi-Facility Location-Allocation Model in the Network

A typical maintenance network is similar to a common service network in components and functional requirements. It normally consists of maintenance demand points, maintenance points, resource supply points, and paths connecting these points [8]. The maintenance network design aims to determine the location, the number, the guaranteed area, and the maintenance capability of maintenance points [9]. Therefore, the regionalized URT maintenance network design can be attributed to the service network design issues [10], i.e., the multi-facility location-allocation problem. Its basic model can be summarized as four classical ones: the P-center, the P-median, the set coverage, and the maximum coverage models [11]. They embody the requirements of different service objects. The P-center model focuses on the emergency facilities planning. The P-median model aims to layout the facilities with the shortest overall travel distance, which reflects the operating efficiency of the network. The maximum coverage model can obtain the sites by covering the most demands with a limited number of facilities, but the remaining demands may not be served. The set coverage model indicates minimal network construction costs by covering all demand points with the least facilities within the specified coverage radius or response time [12].

In practice, the crucial requirements of the URT maintenance network in this paper are summarized as follows: (1) All demands, including all nodes and edges in the whole URT network, should be fully covered with a minimum number of maintenance points. (2) Emergency response function to unexpected failures should be considered while maximizing the routine inspection and maintenance efficiency. (3) Differences in the importance of nodes need to be reflected in the maintenance network, that is, important nodes are given priority. (4) The amount of maintenance resources configured for the maintenance points meets the random maintenance demands as a result of unexcepted failures. Therefore, a highly reliable maintenance network is needed to enhance the robustness of the URT network to various attacks. This research attempts to integrate the P-median model with the set coverage model to build a regionalized URT maintenance network design model for solving the URT-MNDP. The integrated model does nearly all requirements mentioned above.

The P-median model and set coverage model have been widely used and developed in the field of various service networks since they were proposed [13,14]. For the P-median model, Kung-Jeng Wang et al. [15] considered random demands and limited facility capacities, established a two-level stochastic programming model by developing the P-median model to maximize benefits within the supply chain network. As a result, suitable locations of facilities and the assignment of tasks are obtained by solving the model. Yu An et al. [16] built a set of two-stage robust optimization models to design reliable P-median facility location networks. Two practical scenarios are then applied to demonstrate the strong modeling capability of the framework, i.e., facility capacity and demand change due to site disruption. Li Wang et al. [17] formulated a two-tier multi-objective location-allocation decision model with P-median for medical facilities under random treatment needs, limited resources and costs, different traffic environments, and so on. Xiaolin Sun [18] considered the probability of node emergencies, established the average optimization model based on the P-median model, and a feasible layout of emergency rescue stations for the URT system is obtained in the research. However, valid solutions to various facility location problems are obtained by the p-median model in the above literatures, where the number of facilities is determined in advance, which may not necessarily meet the requirements of service quality or cause a waste of resources [19].

For the set coverage model, it was employed independently or in combination with other models to solve the network facility location problem and achieved good results. Farahani et al. [14] gave much more influential reviews of set coverage models and their practical application. Sávio S. V. [20] considered the gas diffusion characteristics and detector coverage rules, integrated the gas diffusion data of chemical plants into a 0-1 integer programming model based on the set coverage model, and obtained the minimum number of gas detectors and its optimal placement. The same kind of research can be seen in the study [21]. Baofeng Sun et al. [22] developed a novel bi-objective model by modifying the set coverage model to design the URT maintenance network. The model aims to minimize the number of maintenance points and the total length of paths under a variable coverage radius. However, it fails to pay attention to the importance of nodes in the network. Erdemir E. T. et al. [23] determined the location of the transfer point for the ambulance and the air ambulance helicopter by both usages of the set coverage model and a maximum coverage model. Although the set coverage model can determine the minimal number of facilities, it cannot guarantee the shortest travel distance. End to end, Sittipong Dantrakul et al. [24] separately established the improved set coverage model (M1) and P-median model (M2) for joint decision-making issues of the open facilities location and customer allocation. Numerical simulations show that M1 has better performance under the condition of higher construction costs, and under higher transportation cost, M2 shows better performance.

Stepping in combination with the P-median model and set coverage model, few literature-related works can be found. Lin Ye et al. [19] suggest implementing a new location planning and assignment model to reduce the number of existing recycling centers in Taiwan by a two-stage integrated model with location set covering and P-median. The actual calculation results show that this integrated model is more efficient than existing models. Another trial research, such as literature [25,26], also investigated the integrated model for the bi-objective capacitated P-median problem with multilevel capacities. Their research contributed to a good way to make use of advantages from these two kinds of models, but did not meet exactly four requirements of the URT maintenance network we study. Oriented to the problems in the field of the URT maintenance network design, the more economical number of maintenance facilities, the more reasonable facility layout and demand distribution can be both obtained by combining the constraints of URT practical problem with the integrated novel model.

2.2. The Method of Allocating Maintenance Resource

Maintenance resources are the collective of maintenance personnel, equipment and tools, spare parts, technical data, and so on required for equipment maintenance. They are the necessary support for implementing maintenance activities [27]. Allocating maintenance resources for the network is the "forward-looking" job of maintenance and management. The methods to optimize the maintenance resources allocation include the Monte Carlo simulation, the methodology of uncertainty theory, the company resource planning, the intelligent optimization method, the multiple hybrid algorithm, etc. Among them, the Monte Carlo simulation method has the advantage with good sample randomness, typical simulation scenarios, and numerical solutions with good statistical characteristics [28]. DuyQuang Nguyen et al. [29] simulated the different failure modes of the equipment through the Monte Carlo method to evaluate the economic loss and expected maintenance cost. The preventive maintenance planning and the amount of maintenance resources needed can be optimized in a process plant. Similarly, Su Sheng et al. [30] optimized the allocation of maintenance resources for the vulnerable portion of the protection system in Huazhong power network. Wang Yulong [31] established a spare parts demand forecast model under the preventive replacement strategy. The common features of these studies are shown that the statistical characteristic values coming from random samples or in different scenarios are obtained by the Monte Carlo simulation. These values are regarded as the approximate numerical solution of the problem instead of that of precise algorithms. This approach significantly benefits the NP-hard resource allocation problem-solving with a couple of uncertainties in real-world cases.

In terms of URT maintenance resource allocation, the mathematical programming model is explored in most literature. Researchers combine historical data with maintenance strategies, tasks, and requirements to allocate maintenance resources in a targeted manner for the URT system.

For instance, Gorman et al. [32] proposed a hybrid constraint planning model and genetic algorithm to allocate maintenance personnel for each railway maintenance station. Pour S.M. et al. [33] divided the URT signal system into several subnets by clustering method and developed a multi-stage constraint planning method to optimize the configuration and scheduling of the maintenance team within each subnet. Lau H. C. et al. [34] proposed an integer linear programming model to deploy security teams for a mass rapid transit network under security-related constraints. Simple randomization strategies are presented to optimize the scheduling of patrol. Haijun Wang [35] formulated an optimization allocation model of maintenance staffs based on "full repair" and an economic inventory model of special parts in full life cycle based on safety stock to optimize the allocation of maintenance labor and material resources for subway vehicles. However, these mathematical programming models in the above studies are not standing at the URT network-wide resource allocation perspective but focusing on resource allocation within specific facilities and equipment. Thus, these models are not entirely adapted to the network-wide resource allocation problem. Another research weakness in practice is shown that the present URT maintenance resource are allocated and managed by line. In this situation, the maintenance resources will be allocated repeatedly and lack of response-ability, and the unified resource allocation requirements are unable to be satisfied perfectly. In order to achieve the goal of managing network resource as a whole and ensure reliability of URT maintenance network, our research tries to apply the Monte Carlo method to conduct a large number of random experiments for reflecting the uncertainty of failures. Furthermore, the maintenance resources are allocated by the maximum possible maintenance demand predicted in the simulation for the network.

In brief, the contributions of this work are four aspects, as follows:

1. A novel URT-NMDP is defined from the network-wide maintenance with an incapacitated constraints perspective.
2. A new multi-objective integer programming model for designing the regionalized maintenance network is established by integrating the set coverage model with the P-median model, and several critical guarantee rules are followed in the model.
3. The reliability problem of the resource allocation is described for the URT maintenance network in a real-world environment by the Monte Carlo simulation.
4. A case study on Changchun city with a developing URT system is given. The performance of the regionalized maintenance network is evaluated from a network-wide maintenance perspective. The applicability of regionalized network-wide maintenance and management mode is analyzed by comparing it with other two modes.

3. Model and Algorithm for the URT-NMDP

3.1. Problem Description

The URT Network-Wide Maintenance Decision-Making Problem (URT-NMDP) in this research, including two critical decisions of designing regionalized the maintenance network and allocating maintenance resource, is described as follows: Facilities and equipment in the whole URT system are taken as the maintenance objective. According to the node importance and maintenance guarantee rules, several appropriate maintenance points are located on the basis of the URT physical network, and each demand point is allocated to a unique maintenance point until all demand points have been assigned. In this way, the network is divided into several non-overlapping and adjacent regional subnets, and every subnet contains only one maintenance point. Maintenance resources are configured for every subnet according to maintenance demands. Consequently, a low-cost, low-energy, high-efficiency, and quick-response regionalized URT maintenance network is constructed to ensure sustainably reliable maintenance and efficiently safe operation of the URT system.

The URT network can be represented as a graph $G = \{V, E\}$, with rail stations defined as the node set V while tracks indicated by the edge set E, $V = \{v|v = 1, 2, \ldots, n\}$, $E = \{e|e = 1, 2, \ldots, l\}$, where n and l represent the number of nodes and edges, respectively. In practice, all nodes and edges in the URT network are maintenance demand points. Let I be the set of maintenance demand points, then $I = G = \{V, E\}$. The maintenance point is an organization that is set at the node to provide maintenance services for demand points, store maintenance resources, and manage maintenance activities. In principle, all nodes in the network are candidates for maintenance points, but the number of nodes actually selected as maintenance points is limited. Let J be the set of maintenance points, then $J \subset V$, and $J = \left\{ j \middle| j = 1, 2, \ldots, p \right\}$, p represents the number of maintenance points. The URT network is an undirected network in this research. Therefore, the maintenance path is defined as the distance d_{ij} between the maintenance point $j \in J$ and the demand point $i \in I$. Let P be the set of maintenance paths, then $P = \left\{ d_{ij} \right\}$, $i \in I$, $j \in J$. The maintenance point set J and the maintenance path set P constitute the maintenance network G', which consists of p non-overlapping and adjacent regional subnets G'_j. That is why G' is called the regionalized URT maintenance network.

Regarding the integrated organization and maintenance requirements for network facilities and equipment, the following hypotheses are proposed in this work:

- The maintenance point is selected among nodes, and the range of its total number is determined in advance based on experience.
- The only maintenance point is deployed for every regional subnet, and each maintenance demand point can be assigned to the only maintenance point. That is, the sole maintenance responsibility rule is followed in the maintenance network.
- The distance between each pair of nodes can be obtained through practical investigation.
- A node and its adjacent edge in the driving direction are collectively called a maintenance demand point. Therefore, the allocation of demand points is mainly calculated according to the node. If the node is assigned to a maintenance point, the corresponding adjacent edge will be assigned to the same maintenance point.
- Large-size and special-purpose maintenance equipment and materials are unitedly configured and managed in a unified manner with the maintenance network; they are not considered in the research. This work mainly configures basic maintenance resources for maintenance points in the regional subnets.
- Each maintenance demand point in the network contains K types of professional equipment, and the corresponding maintenance resources is also divided into K categories. That is, the maintenance resources can complete all tasks with different technical levels, which are uniformly configured by category.
- The failure rate of each demand point is different.
- The average travel speed of maintenance resources from the maintenance point to the maintenance demand point is v_0.
- The maximum failure response time requested by the system is known.

3.2. *Maintenance Guarantee Rule*

3.2.1. Node Importance

In the complex URT network, due to differences in location, degree of connection and environment, the importance of nodes in the network is different from each other [36]. The more important nodes are attacked (equipment failure, traffic control, etc.), the greater impact on the stability of the network and the safety of system operations, making the network show a certain degree of vulnerability [37]. Therefore, in order to improve the overall reliability of the maintenance network and the robustness of the URT network to unexpected failures, based on the weighted network theory, the node importance is used as the weight of each node to calculate the total length of the maintenance path in the whole network. In this way, the maintenance points selected are as close as possible to the important nodes, which meets the maintenance requirement that important nodes are given more attention and more rapid response in the URT system.

The importance of nodes in the complex network is usually measured by centrality indicators of nodes [38], such as degree centrality, closeness centrality, and betweenness. Traditional research applied a single indicator to evaluate the importance of nodes, which only reflects the local characteristics of the node and fails to reveal the global effect. This work refers to the literature [39] and employs weighted centrality to determine the importance of nodes.

$$w_{v \in V} = \alpha D_{v \in V} + \beta C_{v \in V} \tag{1}$$

where $w_{v \in V}$ represents the importance of node $v \in V$ in the URT network; $D_{v \in V}$ denotes the degree centrality of $v \in V$, which is the number of other nodes directly connected to $v \in V$; $C_{v \in V}$ indicates the closeness centrality of $v \in V$, which is the average shortest path length between the node $v \in V$ and other nodes. In the network; α and β, respectively, represent the weight coefficient of $D_{v \in V}$ and $C_{v \in V}$, and they are determined based on the actual decision-making preference. $D_{v \in V}$ and $C_{v \in V}$ are calculated by Equations (2) and (3):

$$D_{v \in V} = \sum_{u \neq v} a_{uv}, \quad v, u \in V \tag{2}$$

$$C_{v \in V} = \frac{n}{\sum\limits_{v \neq k} d_{vk}}, \quad v, k \in V \tag{3}$$

In Equation (2), a_{uv} is a 0–1 variable, if $v \in V$ is connected with the node $u \in V$, $a_{uv} = 1$, otherwise, $a_{uv} = 0$; In Equation (3), d_{vk} represents the distance between $v \in V$ and $k \in V$.

3.2.2. Timeliness of Failure Response

Failure response time t_{ij}, defined as the interval between the time when the maintenance point receives the failure report and the time when the maintenance resources are delivered to the failure point, consists of the preparation time t_0 and travel time t_{ij}^d of maintenance resources, where t_{ij}^d is calculated by Equation (4). The URT maintenance network is expected to consider the emergency response of failure in the network. Therefore, the actual maximum failure response time t_{ijmax} cannot exceed the maximum failure response time t_{max} required by the system, i.e., $t_{ijmax} \leq t_{max}$. It implies the lowest requirements of the system for failure response time and reflects the coverage radius of single maintenance point, such as Equation (5). Therefore, t_{max} is regarded as one of the crucial constraints for dividing the regional subnet in the maintenance network design model.

$$t_{ij}^d = \frac{d_{ij}}{v_0} \tag{4}$$

$$r_j = v_0 \cdot (t_{max} - t_0) \tag{5}$$

3.2.3. The Method of Allocating Maintenance Unit

The basic maintenance unit (hereinafter referred to as the maintenance unit) is defined as the collection of minimum maintenance resources that can complete specific maintenance tasks and achieve the best performance within the specified time. U is used to denote the maintenance unit, containing the minimum maintenance personnel, tools, spare parts, and maintenance materials. The maintenance units keep an active state in the network, they can be dispatched and combined freely according to the different equipment categories, failure types, and maintenance activities. Namely, when there is no failure in the system, maintenance units perform daily works, such as routine inspection and maintenance for professional equipment and spare parts; When the equipment in the network fails, maintenance units are rapidly scheduled to perform corresponding maintenance activities.

We assume that the failure rate of the kth type equipment at $i \in I$ is p_i^k in the work. There are needed U^k maintenance units to repair it when the kth type equipment fails. The Monte Carlo method is employed to simulate the uncertainty of the location of the failure points, and maintenance units are configurated for the maintenance point accordingly. The Monte Carlo failure simulation process is described as follows: (1) For each demand point $i \in I, i = 1, 2, \ldots, N$, given a random number $r \in [0, 1]$, if $r \in [0, p_i^k]$, then $i \in I$ is considered as the failure point. (2) According to the allocation of demand points, the total number of failure points $O_{j,m}^k$ in the G'_j is counted in a simulation. (3) The simulation is performed m = 10,000 times; $O_{j,m}^k$ and their frequency $f_{j,O}$ in the regional subnet G'_j are counted. (4) Maximum $O_{j,m}^k$ among 10,000 simulations is taken as the number of maintenance unit U_j^k configurated for $j \in J$, which can ensure that maximum possible maintenance requirements in the subnet G'_j are fully responded. Therefore, U_j^k is shown as Equation (6), and the maintenance resource R_j in the regional subnet G'_j is defined as the sum of the all type of maintenance units, as shown in Equation (7):

$$U_j^k = O_{j,m}^{kmax} = max(O_{j,m}^k) \tag{6}$$

$$R_j = \sum_{k \in K} U_j^k \tag{7}$$

3.3. Mathematical Model

Focusing on URT-NMDP, the set coverage model and the improved P-median model are integrated to establish a bi-objective 0–1 integer programing model, which is applied to design the regionalized URT maintenance network that aims to achieve trade-off between construction costs and operating efficiency. The mathematical model for URT-NMDP is as follows:

$$F_1 = min \sum_{j \in J} x_j \tag{8}$$

$$F_2 = min \sum_{i \in I,} \sum_{j \in J} d_{ij} \cdot w_v \cdot y_{ij} \tag{9}$$

s.t.

$$y_{ij} \le x_j, \forall i \in I, \forall j \in J \tag{10}$$

$$\sum_{j \in J} y_{ij} = 1, \forall i \in I \tag{11}$$

$$p_{min} \le \sum_{j \in J} x_j \le p_{max} \tag{12}$$

$$t_{ij} = t_0 + t_{ij}^d, \forall i \in I, \forall j \in J \tag{13}$$

$$t_{ijmax} \le t_{max}, \forall i \in I, \forall j \in J \tag{14}$$

$$\sum_{i \in I} z(p_i^k) \cdot y_{ij} \le U_j^k \cdot x_j, \ \forall i \in I, \forall j \in J, \forall k \in K \tag{15}$$

$$\sum_{i \in I} \sum_{k \in K} z(p_i^k) \le R_j, \forall j \in J \tag{16}$$

$$z(p_i^k), \ x_j, \ y_{ij} \in \{0, 1\}, \ \forall i \in I, \forall j \in J, \forall k \in K \tag{17}$$

Objective function (8) roots from the objection of the classic set coverage model. It aims to minimize the number of maintenance points in the network, which means the minimum construction cost and reflects the economic considerations about the network planning. Another objective function (9) is based on the improved P-median model. It aims to minimize the sum of the weighted distances between demand points and maintenance points, which indicates the operating efficiency of the whole network. The node importance is regarded as the weight of the demand point in function (9) to ensure that the location of the maintenance points is as close as possible to the important nodes. By this, the maintenance strategy may show clearer preference attention and more rapid response to those important nodes.

Constraint (10) means that demand points are assigned to candidate node j only when it is selected as a maintenance point. Constraint (11) represents that each demand point $i \in I$ is assigned to the only one maintenance point $j \in J$; that is, there is no repeated maintenance duty in the network. Constraint (12) indicates that although the total number of maintenance points p in the network is unknown, it is required to be within the interval $[p_{min}, p_{max}]$. Constraint (13) represents the actual failure response time t_{ij}. Constraint (14) denotes that the actual maximum failure response time t_{ijmax} in the regional subnet G'_j must not exceed the maximum failure response time t_{max} required by the system. It reflects the coverage area of a single maintenance point and emergency function of the network. Constraint (15) indicates that maintenance units of the kth category equipment configured for $j \in J$ meet the stochastic maintenance demands in the subnet. Constraint (16) means that maintenance resources deployed in a subnet meet the maintenance requirements of all kinds of equipment. Constraint (17) shows that $x_j, y_{ij}, z(p_i^k)$ are 0–1 decision variables, x_j is the location decision variable, if the candidate node j is selected as the maintenance point, $x_j = 1$, otherwise, $x_j = 0$; y_{ij} is the assignment decision variables: if $i \in I$ is assigned to $j \in J$, $y_{ij} = 1$, otherwise, $y_{ij} = 0$; $z(p_i^k)$ is the failure decision variable of the kth category equipment at $i \in I$: when the failure rate is p_i^k, if the equipment fails, $z(p_i^k) = 1$, otherwise, $z(p_i^k) = 0$.

3.4. Solving Algorithm

The mathematical model for URT-NMDP essentially is the decision-making modeling of the multi-facility location-allocation problem. In most previous studies [40,41], heuristic algorithms were used to solve this type of problem, which is a typical NP-hard problem. That is to say, there are no feasible solutions that can be obtained in polynomial time, as the solution search space become huge with the increase in the number of candidate sites. Further, there are two conflicting objectives in the proposed model. Thus, the multi-objective heuristic algorithm should be adopted, which is created to cope with optimization problems with multiple objectives by yielding several trade-off solutions [42]. For both reasons, in this study, the non-dominated sorting genetic algorithm-II (NSGA-II) is employed to solve the proposed model, which is a promising way to solve the multi-objective optimization problem by combining the population-based nature of the genetic algorithm (GA) and Pareto front method [43].

The process of the NSGA-II based algorithm that is applied to solve the developed model is divided into four stages: First, maintenance points are located. The set of demand points I and the set of candidate nodes for maintenance points V are given according to a real-word URT network. Considering node importance and maintenance guarantee rules, several maintenance points that meet the constraints are randomly selected to constitute a maintenance point set J. Second, all demand points are allocated to maintenance points. Under the constraint (14), the coverage radius of every maintenance point is calculated. Maintenance demand points within the radius are assigned to the only maintenance point by the principle of nearby allocation. Third, Maintenance units are configurated for every regional subnet. The entire network is divided into several non-overlapping and adjacent regional subnets through the above two stages, and then the method of allocating a maintenance unit is applied to deploy maintenance resources for every subnet. Fourth, Pareto optimal solutions are obtained through repeated iterations, i.e., the non-dominated sorting operator and the elite selection strategy are employed iteratively to generate the Pareto optimal solution. In the above process, all feasible solutions meet the constraints of the formulated model, and a large penalty is imposed on the solutions that do not meet the constraints.

These processes are achieved through the following specific five steps:

- Step 1: Solution encoding

Considering actual problems, the model and algorithm, we adopt the 0–1 binary encoding method to generate two 0–1 vectors for performing a solution, as Figure 1 shows. Two vectors represent the planning of maintenance points location and corresponding the allocation scheme of demands points respectively. Vector 1 is generated by the 0–1 encoding method randomly, which is shown as a chromosome, i.e., an individual. The gene "$x_j = 1$" in the chromosome indicates that the node j is selected as the maintenance point; otherwise, "$x_j = 0$." Thus, the length of a chromosome implies the number of maintenance points p. Vector 2 is generated according to demand points allocation, where "$y_{ij} = 1$" denotes the demand point i is assigned to the maintenance point j.

0	0	0	0	1	0	…	0
x_1	x_2	x_3	x_4	x_5	x_6	…	x_n

(a) Vector 1

1	1	1	1	1	0	…	0
y_{1j}	y_{2j}	y_{3j}	y_{4j}	y_{5j}	y_{6j}	…	y_{7j}

(b) Vector 2

Figure 1. Coding scheme of a solution.

- Step 2: Initialization

The initial parameters of the model and algorithm are inputted, including n, d_{ij}, w_v, p_i^k, t_{max}, t_0, v_0, $[p_{min}, p_{max}]$, V, the population size NP, the maximum number of iterations *maxgen*, the crossover probability p_c, the mutation probability p_m, and the number of objective functions M, where w_v is normalized. Then, a random initial population that contains NP individuals is generated by the encoding method of Vector 1 and Vector 2 under the constraints (10)–(14), in which the values of two objective functions for every individual are calculated by functions (8) and (9).

- Step 3: Resource allocation

The Monte Carlo method is adopted to simulate the distribution scenarios of failure points in the network. According to the allocation of demand points and simulation results, reliable maintenance units are configured for all regional subnets by Equations (6) and (7) under constraints (15) and (16). Thereby, a complete maintenance network shown by an individual is constructed after this step, which represents a feasible solution of the model, that is, an initial planning scheme of the URT network-wide maintenance.

- Step 4: Non-dominated sorting

The non-dominated solution set in the population is selected based on the values of two objective functions. We record it as the first non-dominated layer, where the non-dominated sorting value of individuals is described as *rank* = 1. Meanwhile, the set is deleted from the population. With the same method, we can select a new solution set that ranks the second non-dominated layer, in which the sorting value of individuals is recorded as *rank* = 2. This step is repeated until all individuals are stratified, and their corresponding ranks are given. Then, the crowding degree value of individuals with the same rank is calculated. The solution set with higher sorting value (such as *rank* = 1) is more excellent in terms of two objective functions. Furthermore, within the same layer, we prefer to select individuals with a lager crowding value to keep the solutions uniform.

- Step 5: Pareto optimal solution under the elite strategy

Some individuals are selected from the initial population by the order of the rank value from top to low and the crowding degree from large to small within the same layer. These individuals constitute a new population by genetic operators, including crossover and mutation. Meanwhile, the two objective function values of new individuals are calculated. Then, the new population is fused with the parent population. "Non-dominant sorting" is implemented in the fusion population, and optimal individuals are selected to constitute the new next offspring population.

The above steps are repeated until the algorithm terminates. The Pareto optimal solutions of the model that balance the two objective functions are obtained. They are Pareto optimal planning schemes of the URT network-wide maintenance with the number and location of maintenance points, the allocation of demand points, and the amount of basic maintenance resources.

4. Case Study

To verify the effectiveness of the model and algorithm proposed in this paper, Changchun City is used as an application case. Compared with other same medium-sized cities in China, its topology structure of the URT network is indeed not complicated, but its network characters are representative, such as in the fast-speed developing stage, and faced with improving the accessibility between districts. Such a network was designed with a priority given to linking the central districts with other districts together to solve the problem of difficult travel for the masses in the surrounding areas of the city. According to complex network theory, the network microscopic characteristics are shown as a lower average degree of network and a larger average shortest path. When network-wide maintenance mode is carried out simultaneously for that kind of network, managers and planners in practice need to ensure whether the short maintenance response time and well accessibility will come true and how many degrees they could be. Therefore, the Changchun URT network is taken as a case study for an in-depth study on modeling and optimization of the maintenance network.

The Changchun urban rail transit planning network is shown in Figure 2, which includes seven lines covering 144 stations and 161 tracks. To facilitate research and description, we number all nodes in the physical network as Figure 2 and calculate the distance between nodes, as shown in Table A1 in Appendix A.

We investigated the construction and service time and the maintenance practice of every URT line in Changchun. According to the results of the investigation, the failure rate is valued as $p^k_{i(1,2,4)}$=0.03 for the kth category equipment in each demand point in line1, line2, and line4; $p^k_{i(3)} = 0.055$ for line3; and $p^k_{i(5,6,7)} = 0.005$ for line5, line6, and line7. Further, considering the features and functions of stations in the URT network as Figure 2, we divide the node set V into four subsets, $V = \{V_1, V_2, V_3, V_4\}$. Let V_1 be the set of the common transit stations, V_2 represents transfer stations set, V_3 denotes the set of start and terminal stations, and V_4 is the set of both the transfer stations and the start and terminal stations, i.e., $V_2 = \{5, 7, 8, 10, 12, 14, 32, 34, 37, 57, 59, 65, 86, 92, 106, 108\}$, $V_3 = \{1, 21, 47, 79, 100, 114\}$, $V_4 = \{4, 22, 26, 39, 48, 77, 81\}$, and other nodes belong to the set V_1. The failure rate of the kth category equipment in different types of maintenance demand points $i \in I$ is calculated by Equation (18):

$$p_i^k = \begin{cases} p^k_{i(u)}, & i \in V_1, u \in \{1,2,3,4,5,6,7\} \\ p^k_{i(u)} + p^k_{i(w)}, & i \in V_2, u, w \in \{1,2,3,4,5,6,7\}, u \neq w \\ 1.2p^k_{i(u)}, & i \in V_3, u \in \{1,2,3,4,5,6,7\} \\ 1.2p^k_{i(u)} + p^k_{i(w)}, & i \in V_4, u, w \in \{1,2,3\}, u \neq w \end{cases} \quad (18)$$

where u, w denote the index of failure rate for various lines.

Figure 2. The planning network of Changchun urban rail transit.

4.1. The Impact of t_{max} on Maintenance Network Desgining

Experiment 1

Purpose: To clarify the impact of the maximum failure response time t_{max} on the planning scheme for the regionalized URT maintenance network.

Parameter: In order to avoid the influence of node importance on the network planning, the importance of each node in the network is set to the same value, i.e., $\forall v \in V, w_v = 1$. t_{max} in the constraint (14) is set to three different values, $t_{max1} = 20$ min, $t_{max2} = 25$ min, and $t_{max3} = 30$ min. The number of maintenance points $p \in [2, 12]$.

Results: The distribution of black squares in Figure 3a–c represents the Pareto front of Experiment 1. Table 1 shows the value of performance evaluation index for the URT maintenance network planning scheme, including the total length of the maintenance path D for the whole network, the average failure response time $\bar{t}$, and the number of maintenance units U_j^k. In Table 1, D is the sum of the distances from all demand points to the nearest maintenance point, calculated by Equation (19); R_D represents the relative change rate of the path length in different scenarios, calculated by Equation (20). In addition, because the URT network contains 7 lines, from an economic perspective, only Pareto optimal solutions whose number of maintenance points does not exceed 7 are analyzed.

$$D = \sum_{i \in V} \sum_{j \in J} d_{ij} \cdot y_{ij} \tag{19}$$

$$R_D = \frac{D_{s-1} - D_s}{D_s} \times 100\% \tag{20}$$

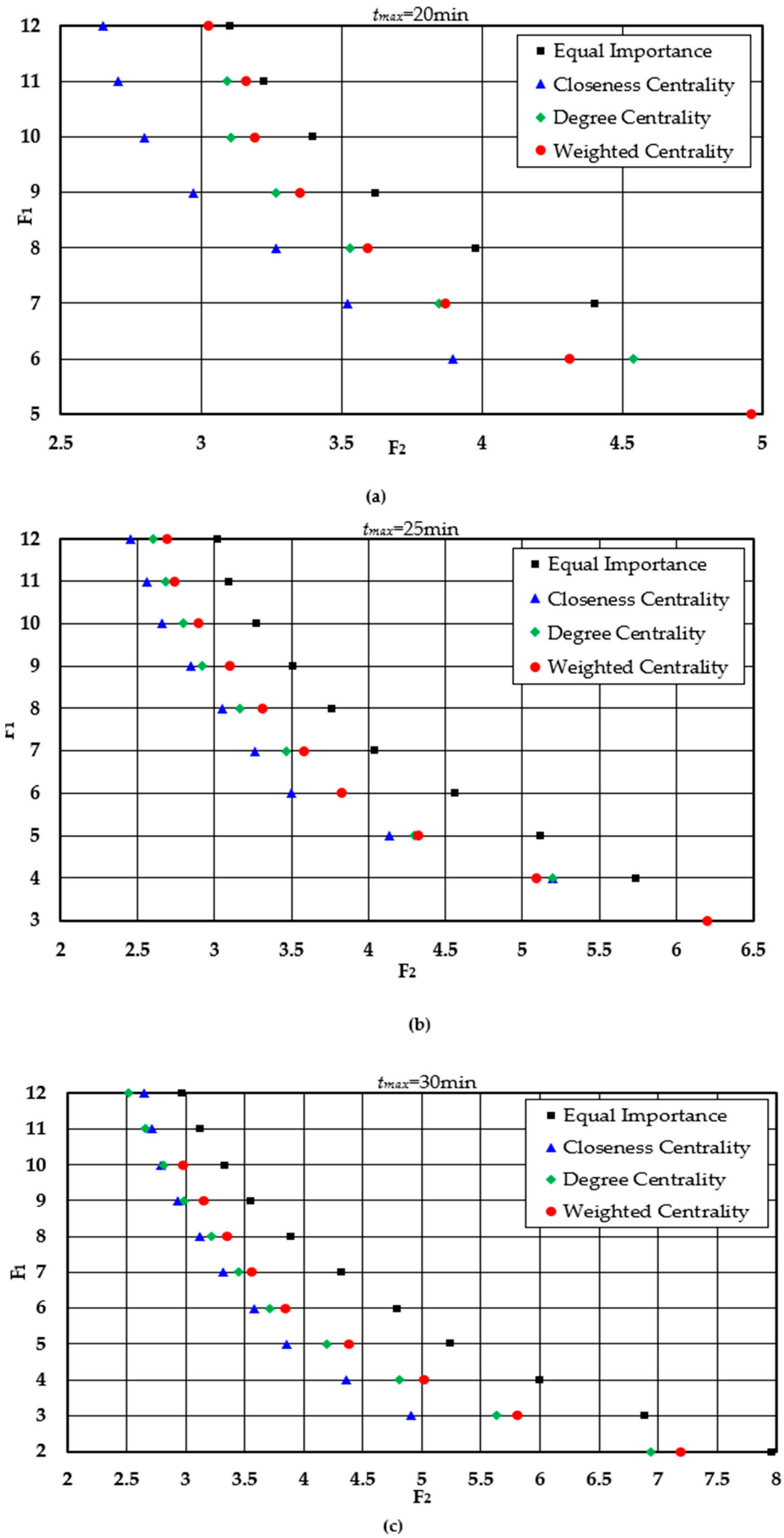

Figure 3. Pareto front distribution of Experiment 1.

Table 1. Performance evaluation of maintenance network for Experiment 1.

F_1	t_{max3} = 30 min				t_{max2} = 25 min						t_{max1} = 20 min					
	F_2	D_3 (km)	$\bar{t}$ (min)	U_j^k	F_2	D_2 (km)	$\bar{t}$(min)	U_j^k	D_2–D_3 (km)	R_D (%)	F_2	D_1 (km)	$\bar{t}$(min)	U_j^k	D_1–D_2 (km)	R_D (%)
2	7.96	1145.90	12.85	19												
3	6.88	991.20	11.47	21												
4	5.99	863.00	10.20	25	5.38	825.90	9.79	24	−31.70	−4.30						
5	5.25	755.40	9.12	27	5.11	736.30	8.80	26	−19.10	−2.53						
6	4.79	690.00	8.57	31	1.56	657.00	8.30	30	−33.00	−4.78						
7	4.31	620.90	8.09	34	4.04	581.60	7.47	31	−39.30	−6.33	4.40	633.70	8.01	35	52.10	8.96

Result analysis: We can observe that the minimum F_1 decreases with t_{max} increase from Figure 3a–c. Specifically, the minimized $F_1 = 7$ under $t_{max1} = 20$ min; the minimized $F_1 = 4$ when $t_{max2} = 25$ min; and the minimized $F_1 = 3$ when $t_{max3} = 30$ min. However, in Table 1, the variation law of D, $\bar{t}$, and U_j^k caused by t_{max} changes is different from the minimized F_1. D, $\bar{t}$, and U_j^k can be reduced only under an appropriate t_{max} constraint, as in the scenario $t_{max2} = 25$ min; An unreasonable t_{max} will increase the value of the above three indicators. For instance, under the same value of the objective function F_1, D_2 in the scenario $t_{max2} = 25$ min is the shortest; it is 4.48% less than D_3 on average and 8.96% less than D_1. Meanwhile, U_j^k and $\bar{t}$ in this scenario are minimal.

From the perspective of the practical URT network-wide maintenance, the shorter D represents the improvement on the operating efficiency of the whole regionalized maintenance network; the less $\bar{t}$ will strengthen the robustness of the URT network to unexpected failures; the less U_j^k indicates the cost savings in the maintenance resources. They reflect the overall performance of the maintenance network.

Therefore, although t_{max} can directly determine the minimized total number of maintenance points, which denotes the lowest construction costs, the performance of the regionalized URT maintenance network is optimal only under a reasonable and tested-in-practice t_{max}. It could also denote, for a real-word project, that managers and decision-makers should balance operating performance and construction costs of the regionalized maintenance network in different scenarios to determine a reasonable requirement for timeliness of failure response. These Pareto optimal solutions the of model for URT-NMDP in various scenarios in our paper may provide reference for managers' decision making.

4.2. The Impact of w_v on the Performance of Maintenance Network

Experiment 2

Purpose: To analyze the influence of the node importance w_v on the performance of the URT network-wide maintenance planning scheme.

Parameter: Under the scenario $t_{max2} = 25$ min, the node importance w_v is assigned four different values, i.e., $w_{v0} = 1, w_{v1} = D_v, w_{v2} = C_v, w_{v3} = 0.5D_v + 0.5C_v$. The scenario $w_{v0} = 1$ is regarded as the basic experiment, it means that all nodes in the URT network are treated equally, and the maintenance demands of important nodes are not considered with a faster response. w_v are normalized. Other parameters are the same as Experiment 1.

Results: The Pareto front of Experiment 2 is shown in Figure 3b. In Table 2, we take the objection $F_1 = 6$ as an example to show the performance evaluation indexes of the planning scheme for regionalized URT network-wide maintenance under the four scenarios. $D_j(i)$ represents the sum of the distances from all maintenance demand points to the maintenance point in the regional subnet G'_j, calculated by Equation (21). R_t denotes the change rate of the average failure response time that other experiments relative to the basic experiment, calculated by Equation (22).

$$D_j(i) = \sum_{i \in I} d_{ij} \cdot y_{ij} \tag{21}$$

$$R_t = \frac{\overline{t_s} - \overline{t_0}}{\overline{t_0}} \times 100\%, \quad s = 1, 2, 3. \tag{22}$$

Result analysis: From Figure 3b, it can be seen that the distribution of Pareto front is fairly uniform under four scenarios, and there are conflicting relationships between F_1 and F_2 that are in accordance with the practice. This indicates that the designed model, algorithm, and scenario experiment are effective in our paper. From Table 2, we can observe that the regionalized URT network-wide maintenance planning scheme and its operating efficiency are sensitive to changes in w_v. In terms of evaluation indicators about operating efficiency D and $\bar{t}$ of the regionalized URT maintenance network, the maintenance planning scheme is optimal under Scenario 4, and it is the worst under Scenario 3. D in Scenario 2 and 4 are reduced by 4.77% and 5.45%; $\bar{t}$ are reduced 0.12% and 2.33%, compared to Scenario 1, respectively. D is the longest in Scenario 3 among four scenarios, i.e., 692.5 km, which is an increase of 5.40% (35 km) compared to the basic Scenario 1. Correspondingly, $\bar{t}$, t_{ijmax}, U_j^k are also maximum. Additionally, U_j^k is not sensitive to the change in w_v, but it is also minimal due to the superiority of the planning scheme of maintenance network under Scenario 4. The reduction of U_j^k in Scenario 4 is 4 compared with Scenario 1.

In fact, these indicators reflect the difference in the distribution of maintenance points and the assignment of demand under varies scenarios. In Scenario 1, all nodes are treated equally; the layout of maintenance points in the entire network is relatively uniform. The divided regional subnets meet the basic maintenance requirement, but there are no outstanding advantages in the network operating performance. In Scenario 2, D_v is taken as the weight of node, leading several maintenance points located at the hub nodes, such as maintenance points 34, 39, 59, and 72. The failure at hub nodes can be quickly responded, and operating performance of the whole maintenance network is second among four scenarios. In Scenario 3, C_v is employed as the weight of node, so that the maintenance points are concentrated in the relatively central area of the URT network, resulting in the longest D. In detail, the maintenance point 88 covers the most demand points, and $D_{88}(i) = 281.0$ km is the longest among all subnets. The performance of maintenance network under Scenario 3 is the worst. In Scenario 4, $w_{v3} = 0.5D_v + 0.5C_v$, the weighted importance is used as the weight of nodes, which makes the layout of maintenance points and the distribution of demand points more reasonable, with minimal D and $\bar{t}$. Moreover, failures of importance nodes are taken into consideration to respond quickly under Scenario 4.

Clearly, the regionalized network-wide maintenance schemes for URT-NMDP designed by the presented model and algorithm in this paper are valid. The scheme under Scenario 4 shows optimal operating performance and is in line with actual URT network-wide maintenance requirements.

Table 2. Performance evaluation of the network-wide maintenance schemes for Experiment 2.

Scenarios	j	$G_j^{'}(i)$	n	$D_j(i)$ (km)	$\bar{t}$ (min)	t_{ijmax} (min)	U_j^k	R_D (%)	R_t (%)
Scenario 1 $w_{v0} = 1$	18	13,14,15,16,17,18,19,20,21,123,124,125.	12	45.90	7.46	12.14	4		
	38	35,36,37,38,39,40,41,42,43,44,45,46,47,48,80,81,82,83, 84,85,86,87,101,102,139,140,141,142,143,144.	30	143.50	8.83	21.29	6		
	53	1,2,3,4,5,6,7,8,9,27,28,29,30,31,32,33,34,49,50,51,52,53,54,55,103, 104.	26	99.30	7.46	14.43	6		
	74	67,68,69,70,71,72,73,74,75,76,77,78,79.	13	45.10	6.96	12.29	5		
	93	63,64,65,66,88,89,90,91,92,94,95,96,97,98,99,100,126, 127,128,129,130,131,132.	24	102.70	8.11	14.57	6		
	136	10,11,12,22,23,24,25,26,56,57,58,59,60,61,62,105,106, 107,108,109,110,111,112,113,114,115,116,117,118,119, 120,121,122,133,134,135,136,137,138.	39	220.50	10.07	19.29	5		
Network		-	**144**	**657.00**	**8.15**	**21.29**	**32**		
Scenario 2 $w_{v1} = D_v$	**34**	1,2,3,4,5,6,7,8,9,10,29,30,31,32,33,34,35,36,49,50,51,52,53,54,55,80,101,102,103,104,105,139,140.	33	127.70	7.53	15.29	7		
	39	37,38,40,41,42,43,44,45,46,47,48,81,82,83,84,85,86,87, 141,142,143,144.	23	105.40	8.55	19.14	6		
	59	11,12,13,56,57,58,59,60,61,62,63,64,106,107,108,109, 110,111,112,113,114,120,121,122,123,137,138.	27	104.10	7.51	13.57	5		
	72	67,68,69,70,71,72,73,74,75,76,77,78,79.	13	55.60	8.11	14.14	5		
	92	14,15,16,17,18,19,20,21,65,66,88,89,90,91,92,93,94,95, 96,97,98,99,100,124,125,126,127,128,129,130,131,132.	32	171.60	9.66	23.00	6		
	116	22,23,24,25,26,27,28,115,117,118,119,133,134,135,136.	16	61.20	7.46	13.14	3		
Network		-	**144**	**625.60**	**8.14**	**23.00**	**32**	**−4.77**	**−0.12**
Scenario 3 $w_{v2} = C_v$	14	11,12,13,14,15,16,17,18,19,20,21,122,123,124,125,126.	16	58.50	7.22	15.57	5		
	33	6,7,8,9,27,28,29,30,31,32,33,34,35,50,51,52,53,54,55,56,103,104.	22	61.10	5.97	10.43	6		
	82	11,12,13,56,57,58,59,60,61,62,63,64,106,107,108,109, 110,111,112,113,114,120,121,122,123,137,138.	29	156.50	9.71	24.29	6		
	88	1,2,3,4,5,36,37,38,39,40,41,42,43,44,45,46,47,48,49,80, 81,83,84,85,101,102,143,144.	**41**	**281.00**	11.79	25.00	8		
	107	10,58,59,60,61,62,105,106,107,108,109,110,111,112,113,114,121,137,138,139.	20	81.70	7.88	15.57	4		
	118	22,23,24,25,26,57,115,116,117,118,119,120,133,134,135,136.	16	53.70	6.80	13.43	4		
Network		-	**144**	**692.50**	**8.22**	**25.00**	**33**	**5.40**	**0.86**
Scenario 4 $w_{v3} = 0.5D_v$ $+0.5C_v$	14	11,12,13,14,15,16,17,18,19,20,21,62,63,123,124,125,126.	18	69.60	7.52	15.57	5		
	34	1,2,3,4,5,6,7,8,9,10,27,28,29,30,31,32,33,34,50,51,52,53,54,55,56,57,102,103,104,105,106,107,137,138.	34	131.60	7.53	15.29	7		
	37	35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,65,66,67, 80,81,82,83,84,85,86,87,101,139,140,141,142,143,144.	33	**159.00**	8.88	22.71	6		
	75	68,69,70,71,72,73,74,75,76,77,78,79.	12	40.10	6.77	12.29	4		
	120	22,23,24,25,26,58,59,60,61,108,109,110,111,112,113, 114,115,116,117,118,119,120,121,122,133,134,135,136.	28	146.40	9.47	17.43	4		
	127	88,89,90,91,92,93,94,95,96,97,98,99,100,127,128,129, 130,131,132.	19	74.50	7.60	13.14	4		
Network		-	**144**	**621.20**	**7.96**	**22.71**	**30**	**−5.45**	**−2.33**

4.3. Adaptability Analysis of the Regionlized Network-Wide Maintenance Mode

According to the division mode of the duty unit, the existing old and new maintenance and management modes of URT systems can be divided into three types. This section compares and analyzes the maintenance effectiveness and adaptability of the three modes.

Maintenance and management mode by line (M_1): The line is taken as the management unit in this mode, the maintenance point located at each line is responsible for responding to maintenance demands, configurating and storing maintenance resources, and managing maintenance activities within the line.

Single-center comprehensive maintenance and management mode (M_2): The only comprehensive maintenance point is arranged to be responsible for the inspection, maintenance, and repair of all equipment and facilities in the whole URT network.

Regionalized network-wide maintenance and management mode (M_3): The entire URT network is divided into several regional subnets in this mode, where every subnet consists of the only maintenance point and many potential demand points, and the reliable maintenance resources are allocated at the maintenance point to strengthen the robustness of the network to random failures.

For M_1 and M_2, Equation (1) is applied to calculate the importance of node in the lines and network. Then, the nodes with higher importance are adjusted as the maintenance points. To ensure the same number of maintenance points as M_1, the regionalized maintenance scheme under the designated scenario $t_{max1} = 20$ min, $w_{v3} = 0.5C_v + 0.5D_v$, $F_1 = 7$, $F_2 = 3.869$ is taken as the object of comparison. The maintenance schemes and their performance evaluation indexes under three modes are shown in Tables 3 and 4. We regard M_1 as the basic mode in this part, and R_U calculated by Equation (23) denotes the relative change rate of U_j^k.

$$R_U = \frac{U_{j,M_s}^k - U_{j,M_1}^k}{U_{j,M_1}^k} \times 100\%, \quad s = 2, 3. \tag{23}$$

Table 3. Maintenance scheme and its performance evaluation for M_1.

Mode	*Object*	j	n	$L_j(e)$ (km)	$D_j(i)$ (km)	U_j^k	$\bar{t}$ (min)	t_{ijmax} (min)
M_1	line1	11	21	26.50	146.10	5	11.94	22.29
	line2	18	37	37.00	222.80	5	14.24	27.86
	line3	12	35	37.60	279.30	8	14.47	29.14
	line4	88	25	23.60	126.50	5	10.61	18.29
	line5	106	18	19.80	79.30	2	10.09	17.14
	line6	124	23	29.60	139.50	4	13.07	21.57
	line7	138	19	22.50	71.50	2	10.52	16.57
	Network	**-**	**144**	**196.90**	**1065.00**	**31**	**12.13**	**29.14**

Table 4. Maintenance schemes and their performance evaluation for M_2 and M_3.

Mode	j	n	$L_j(e)$ (km)	$D_j(i)$ (km)	U_j^k	$\bar{t}$ (min)	t_{ijmax} (min)	R_D (%)	R_t (%)	R_U (%)
M_2	**10**	**144**	**196.60**	**1322.80**	**14**	**15.12**	**32.29**	**24.21**	**24.65**	**−54.84**
M_3	7	30	41.50	109.50	7	7.21	12.00	**−40.14**	**−32.65**	**9.68**
	40	13	20.30	54.90	4	8.03	17.57			
	72	12	14.70	48.90	3	7.82	14.14			
	105	21	29.10	106.0	5	9.21	18.43			
	117	17	25.10	65.20	4	7.48	13.29			
	126	31	37.10	183.00	6	10.43	19.29			
	140	20	28.80	70.00	5	7.00	11.00			
	Network	**144**	**196.60**	**637.5**	**34**	**8.17**	**19.29**			

Firstly, compared Table 3 with Table 4, under the same number of maintenance points, i.e., p = 7 in M_1 and M_3, operating performance and resources costs of the maintenance network under M_3 are better. Compared with M_1, D in M_3 reduced by 40.14% (427.5 km), $\bar{t}$ reduced by 32.65 (3.96 min), and U_j^k increased by 9.68% (3). Secondly, its construction costs and resource investment for maintenance network are the lowest among three modes, as there is the only maintenance point in M_2. Compared with M_1, U_j^k under M_2 reduced by 54.84% (17). However, maintenance efficiency of the scheme under M_2 is the worst. Compared with M_1, D and $\bar{t}$ increased by 24.21% and 24.65% under M_2, respectively. D under M_2 is more than twice that of M_3. These characteristics of M_2 are indeed unfavorable to maintain the sustainable development of the maintenance network. Thirdly, the performance and investment cost of the maintenance scheme under M_1 are between M_2 and M_3. U_j^k under M_1 is close to that of M_3, its D and $\bar{t}$ are more than M_3, but less than M_2.

Consequently, from the perspective of the trade-off between maintenance cost and efficiency, if it can meet the maintenance requirements of the small-size network, M_2 is a good choice. As the URT network expands, M_2 may be applied as a transition mode to M_3 or combined with other modes to avoid adverse effects caused by its drawbacks. M_1 is suitable for the early operation of URT and the initial stage of networking operation, in which there are a few lines in the URT network. Moreover, M_1 has unique advantages in these situations, such as clear duty division and a convenient management method for maintenance resources and activities. With the expansion of the URT network and the gradual maturity of the networking operation technology, M_1 highlights its lack of overall benefits. In this situation, M_3 in this study is more effective; it is not only conducive to saving maintenance resources, but also improving security and reliability of the URT network. Meanwhile, the overall maintenance efficiency of M_3 is highest under the same cost, that is, its cost–benefit output is optimal in highly networking URT network.

5. Conclusions

In this study, we proposed a novel URT-NMDP to fill the corresponding research gap. In particular, in order to solve this problem, we explored a bi-objective 0–1 integer programming model to design the regionalized URT maintenance network that balanced investment cost and operating efficiency. We designed the NSGA-II-based algorithm that can effectively balance the two conflicting objective functions for the problem, and obtained the Pareto optimal solutions that meet the real-world maintenance requirements. Additionally, we drew attention to the problem of allocating maintenance resources for the URT network. Considering the uncertainty of the failures in the URT network, we presented the Monte Carlo simulation method to allocate maintenance units for the regionalized URT maintenance network developed in this research.

Numerical experiments on Changchun UTR demonstrated that the regionalized URT maintenance network has higher operating efficiency on the premise of a reasonable requirement for the maximum failure response time. The URT network-wide maintenance scheme developed under the weighted importance of nodes not only provided the best maintenance performance, but also gave the important nodes more attention. Further, compared with the other two modes, the regionalized URT network-wide maintenance and management mode studied in this research is more applicable to maintain the URT network with highly networking degree. As a whole, we provide an adequate methodology and effective reference for maintenance and management decision-making about URT network facilities and equipment. From the practical perspective, decision-makers need to choose the maintenance mode that matches the development of the URT network based on this research. Moreover, some crucial factors should be considered when there will be a need to construct a regionalized URT maintenance network, such as the trade-off between maintenance cost and efficiency, the reasonable emergency requirements, and importance characteristics of nodes in basic URT network.

A clear direction of future research is to focus on the maintenance of vulnerable nodes from the node importance perspective. Multiple dynamic factors should be comprehensively considered for those vulnerable nodes in order to construct a more efficient URT maintenance network, such as site passenger flow, location, and the surrounding environment. Deeper considerations in network-wide perspective, those impacts coming from passenger flow distributions in the disequilibrium URT network, are highlighted to be developed instead of functional maintenance network design. Moreover, in real practice, one delay of maintenance or repair can cause those connected path failures in the URT network. Hence, another interesting direction is to extend the maintenance network design problem into a multi-level formulation of robust service network design problem to support URT networked operation safety.

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Appendix A

Table A1. Length of each track in Changchun URT network (km).

Line 1	Line 2	Line 3		Line 4	Line 5	Line 6	Line 7
(1,2) = 1.4	(22,23) = 1.7	(48,49) = 1.2	(68,69) = 1.2	(4,80) = 1.3	(81,101) = 1.1	(26,115) = 1.2	(22,133) = 1.6
(2,3) = 1.2	(23,24) = 1.1	(5,49) = 1.4	(69,70) = 0.9	(48,80) = 1.1	(101,102) = 1.1	(115,116) = 1.0	(133,134) = 1.6
(3,4) = 1.4	(24,25) = 2.0	(5,50) = 1.6	(70,71) = 1.2	(48,81) = 0.9	(7,102) = 1.1	(116,117) = 0.9	(134,135) = 1.6
(4,5) = 0.7	(25,26) = 1.7	(50,51) = 1.2	(71,72) = 1.2	(81,82) = 1.4	(7,103) = 0.9	(117,118) = 1.2	(118,135) = 0.9
(5,6) = 0.9	(26,27) = 2.0	(51,52) = 0.6	(72,73) = 1.1	(37,82) = 1.1	(34,103) = 1.4	(118,119) = 1.4	(118,136) = 1.4
(6,7) = 1.4	(27,28) = 1.2	(52,53) = 0.6	(73,74) = 1.6	(37,83) = 0.9	(34,104) = 1.1	(119,120) = 1.4	(57,136) = 1.4
(7,8) = 1.2	(28,29) = 1.2	(32,53) = 1.1	(74,75) = 1.1	(83,84) = 0.9	(104,105) = 1.6	(108,120) = 1.7	(57,137) = 1.2
(8,9) = 1.4	(29,30) = 0.9	(32,54) = 0.9	(75,76) = 0.9	(84,85) = 0.7	(105,106) = 0.9	(108,121) = 1.4	(106,137) = 1.2
(9,10) = 1.6	(30,31) = 0.9	(54,55) = 0.7	(76,77) = 0.9	(85,86) = 0.7	(106,107) = 1.1	(121,122) = 1.2	(106,138) = 0.9
(10,11) =1.1	(31,32) = 1.0	(55,56) = 0.9	(77,78) = 1.1	(86,87) = 1.1	(59,107) = 1.4	(122,123) = 2.1	(10,138) = 1.8
(11,12) =1.1	(32,33) = 0.7	(56,57) = 0.9	(78,79) = 1.8	(65,87) = 1.4	(59,108) = 1.9	(123,124) = 0.7	(10,139) = 1.2
(12,13) =1.6	(33,34) = 1.0	(57,58) = 1.1		(65,88) = 0.7	(108,109) = 1.9	(124,125) = 0.7	(139,140) = 0.9
(13,14) =2.0	(8,34) = 1.5	(58,59) = 1.6		(88,89) = 0.9	(109,110) = 0.7	(14,125) = 1.0	(86,140) = 1.4
(14,15) =1.4	(8,35) = 1.1	(59,60) = 0.9		(89,90) = 1.4	(110,111) = 0.9	(14,126) = 2.6	(86,141) = 0.9
(15,16) =1.2	(35,36) = 1.0	(60,61) = 0.9		(90,91) = 1.4	(111,112) = 0.9	(92,126) = 2.6	(141,142) = 0.9
(16,17) =1.4	(36,37) = 1.5	(61,62) = 0.7		(91,92) = 1.1	(112,113) = 0.9	(92,127) = 1.2	(142,143) = 1.8
(17,18) =0.7	(37,38) = 1.0	(12,62) = 1.2		(92,93) = 0.9	(113,114) = 0.9	(127,128) = 1.4	(143,144) = 0.9
(18,19) =1.6	(38,39) = 1.5	(12,63) = 1.2		(93,94) = 0.9		(128,129) = 0.7	(39,144) = 0.9
(19,20) =1.2	(39,40) = 1.1	(63,64) = 1.2		(94,95) = 0.9		(129,130) = 0.9	
(20,21) =2.0	(40,41) = 1.5	(64,65) = 1.2		(95,96) = 0.7		(130,131) = 1.7	
	(41,42) = 2.0	(65,66) = 1.2		(96,97) = 0.7		(131,132) = 0.9	
	(42,43) = 2.0	(66,67) = 1.2		(97,98) = 0.7		(77,132) = 1.7	
	(43,44) = 1.7	(67,68) = 1.1		(98,99) = 0.7			
	(44,45) = 2.0			(99,100) = 1.1			
	(45,46) = 1.7						
	(46,47) = 2.0						

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