SCHEDULING OF METROPOLITAN RAILWAY FACILITY MAINTENANCE WORKS

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Abstract - In this study, we have developed a scheduling model for the maintenance of metropolitan railways to assist planning staff in efficiently scheduling maintenance work at facilities on site. The model is constructed using mathematical programming techniques with the aim of minimizing maintenance costs subject to the relevant operating constraints required in practice. The model can be efficiently and optimally solved using mathematical programming software, such as CPLEX. To evaluate the performance of the scheduling model in a realistic environment, we conducted numerical tests using practical data from an operation company in Taiwan. The preliminary test results indicate that the proposed model performs well and could be a useful tool for planning staff to efficiently and effectively schedule their maintenance work.

Keywords - Maintenance Scheduling; Metropolitan Railway; Time-Space Network; CPLEX.

I. INTRODUCTION

Currently, maintenance work scheduling in Taiwan is typically based on staff planning experience, which relies on a trial-and-error approach and lacks systematic analysis and efficiency. This method does not provide sufficient systemization or comprehensiveness to organize the manpower demands for troubleshooting duties in the event of facility failure. However, when equipment failure occurs during operations, maintenance staff must be urgently dispatched to troubleshoot, repair, and inspect the equipment to minimize the impact on MRT operations. To reduce the overall cost of maintenance, we have developed a strategy that involves requiring maintenance staff belonging to the same plant to carry out emergency maintenance work. We have also developed a model that uses time and space network flow technology to create a systematic and efficient maintenance schedule for metropolitan railway facilities. This model takes into account preventive maintenance needs, estimated troubleshooting demands, and existing manpower constraints, including the requirement for certified maintenance staff, with the aim of minimizing the overall maintenance cost.

Many studies devoted to investigating maintenance scheduling for metropolitan railway facilities focused on one kind of railway facility and maintenance scheduling for railway facilities integrated with operations. For example, Peng et al. (2011) focused on the problem of scheduling track maintenance, taking into account the mutual exclusion of maintenance work under time and priority constraints while minimizing overall travel costs for the maintenance team and the influence of maintenance projects on railway operations. They set up a large-scale track maintenance scheduling model and developed a heuristic algorithm for solving the model. Pargar (2015) focused on the scheduling of renewal tasks and preventive maintenance in multi-unit systems for railway track maintenance, considering the constraints of time and replacement costs before the next maintenance work and renewal tasks, in order to minimize costs. They constructed a binary integer linear programming model that minimizes renewal costs and downtime within a planned period. They developed a heuristic algorithm for solving the scheduling problems using a decomposition method. Pour et al. (2018) aimed to construct a scheduling problem for preventive maintenance personnel for a signaling system in the Danish railways. They considered the relationship of time between actual schedules, the assignment of cross-day tasks, required staff abilities, and other management constraints to formulate a multi-objective mixed-integer optimization problem. They used a warm-start mixed-integer programming solver to solve the problem with the goal of arriving at the lowest number of working days, the most tasks to be completed, and the lowest cost for assigning a specific task to a project.Zhang et al. (2020) developed a cooperative optimization model to address the challenge of scheduling train operations and maintenance in a dual-track railway network. They aimed to overcome the issue that the downstream and upstream trains are independent, and that maintenance works in a zone cannot be interrupted or split. To solve this problem, the researchers used Lagrangian relaxation to develop a solution algorithm for the model.

Currently, there have been only a few studies that specifically address the overall maintenance scheduling of MRT facilities.For example, Budai et al. (2006) have pointed out that railways require a significant amount of preventive maintenance to

protect against unexpected failures, making the problem essential to schedule preventive maintenance. Short-term preventive maintenance and long-term improvement projects must be scheduled at specific times to reduce inconvenience to passengers and operating costs. The study proposes a mathematical model that utilizes a greedy heuristic for solving the scheduling problem. Finally, the performance of their heuristic algorithm is evaluated by means of randomly generated examples to find optimal solutions. Baldi et al. (2016) constructed a linear mathematical model for a Stochastic Tactical Railway Maintenance Problem. They used a rolling horizon approach each month for dividing the stochastic problem into deterministic sub-problems, and then developed heuristic algorithms, such as a greedy random adaptive search procedure and a genetic algorithm, to solve these problems efficiently. Liu et al. (2020) divided long-term scheduled multi-system maintenance tasks into regularly scheduled tasks and added project tasks. They then constructed an integer programming model to minimize maintenance costs and penalty costs based on the execution cycle, possession duration, and range of influence. To address conflicts for the constraints of temporal and spatial possession, an indicator for possession duration was introduced. Finally, they demonstrated the practicability and availability of the model with a case study.

The time-space network model is suitable for solving routing and scheduling problems, and there are many good applications in the literature. This study will consider the operational constraints in time and space to effectively schedule maintenance teams for short-term maintenance of railway facilities.Hence, it is proposed that the technique of time-space network be used to create the maintenance scheduling model for railway facilities. Regarding the fact that different problems have different characteristics and constraints, different time-space networks will be developed. Therefore, this section contains a review of some of the literature related to the application of time-space networks for solving scheduling problems as a reference for this study. Yan et al. (2014) discussed the scheduling and planning problem in relation to emergency highway repair projects, with consideration of the factors of large-scale supply and disturbance of demand. They applied the time-space network technique to construct a highway emergency repair project scheduling model for determining the movement of work teams. They used the ant colony algorithm to propose a hybrid global search algorithm to solve the problem. Chen et al. (2019) focused on the taxi pooling scheduling problem andused the space-time network technique to construct an integer programming model with the goal of minimizing cost while considering operational constraints, stochastic travel times, and passenger demands.They developed a solution algorithm that solves the integer programming model.

The study's focus is on short-term planning and aims to construct a maintenance scheduling model that minimizes the cost of maintenance for MRT facilities using mathematical programming methods coupled with a space-time network technique. The model is expected to be a useful tool for planners in making more effective maintenance scheduling by optimizing the use of existing resources.

II. MODEL FORMULATION

In this study, we focus on developing a maintenance scheduling model that takes into account preventive maintenance demand, estimated demand for troubleshooting, and operational constraints. These constraints include the maximum number of work teams per site, shift plans, outsourcing contracts, and maintenance skill licensing. To achieve this, we will use mathematical programming methods coupled with the time-space network technique to construct the model. The primary goal of the model is to minimize maintenance costs while effectively utilizing existing resources. The construction of the model is further discussed in the following sections.

2.1 Basic assumptions and given information

The following assumptions and given information, based on the real practices of a Taiwanese metro company, are used to efficiently develop the model and properly define the limitations of its use.

(1)In this study, the maintenance work for the MRT system is divided into four types of work order. The first type is regular planned maintenance work for which the responsible maintenance subsection, necessary maintenance time, and cost are known. The second type is corrective maintenance, which is executed by Company A's staff, while the third type is outsourced supporting maintenance, which is done based on contractual agreements.Therefore, the responsible maintenance subsection (layer)/outsourced supporting manufacturer, the maintenance location (site), the type of maintenance, the date the maintenance is to be performed, the direct cost of each maintenance task, and the contractual price for outsourced supporting maintenance are known.The fourth type of work order relates to emergency maintenance, which has a major impact on operational safety or passenger services in the event of equipment failure. Maintenance teams from the relevant subsections within the same plant must arrive at the site immediately and complete the emergency maintenance within two hours after receiving the notification from the Operational Control Center (OCC) controllers.The location of the emergency maintenance, the type of troubleshooting, the subsections that can execute emergency maintenance,

and the cost of emergency maintenance are known information.

(2)In practice, Company A carries out preventive maintenance of facilities in accordance with government regulations and recommendations from the equipment manufacturer. According to practical needs, we distinguish four types of work orders for preventive maintenance: monthly, quarterly, semi-annual, and annual regular maintenance. In addition, the rolling stock also requires daily inspection, weekly maintenance, biweekly maintenance, and so on. Since the scheduling for the maintenance of rolling stocks and depot equipment is tied to the timetable of MRT operations, the scheduling for this maintenance is not included in this study but could be a topic for future research. There are several periodic types of maintenance that need to be conducted, including daily, weekly, biweekly, monthly, quarterly, semi-annual, annual, 3-year, and 6-year maintenance. However, this study is only concerned with facility maintenance and does not include rolling stock and depot equipment. Therefore, only monthly, quarterly, semi-annual, and annual maintenance need to be considered.

(3)Each maintenance subsection has a given number of maintenance work orders for each site every week, and, according to the operational characteristics, the time for the execution of maintenance is mainly allocated to late-night non-business hours. However, as the staff is on standby for emergency maintenance during operating hours, they are only responsible for a portion of the maintenance work. As a result, the night shift of each maintenance subsection is presently responsible for half of the total number of work orders for preventive maintenance each day. The other half is divided between the other two shifts that coincide with operating hours, with each shift being responsible for 1/4 of the total number of work orders. However, this allocation may be subject to change in the future, depending on operational and maintenance strategies.The areas of responsibility and/or skills of the staff in each maintenance subsection are different. Therefore, the staff members in each subsection usually cannot provide support for the maintenance responsibilities of staff in other subsections.

(4)The planning period is one week. Company A develops an annual maintenance plan every year, so the demand for manpower for preventive and corrective maintenance is similar each month. In practice, the maintenance schedule is planned based on the major activities of Company A, considerations for facility failures and personnel attendance, outsourced contract costs, and necessary operational constraints. These factors may alter the maintenance schedule each week.Although the planning period for this study is one week, in practice this period is flexible and may be adjusted in the future. However, for the purposes of this study, the shift schedule for maintenance staff is fixed at three shifts per day within the planning period.The main task of the maintenance staff is to perform preventive maintenance on the facilities. Additionally, they need to be on standby to carry out emergency maintenance as soon as they are informed by the controller at the OCC in the event of equipment failure or other issues.The morning shift is from 07:00 to 15:00, the afternoon shift is from 15:00 to 23:00, and the night shift is from 23:00 to 07:00. In this study, the starting time for maintenance work each day is 23:00.

(5)Typically, events that result in severe damage or long-term operational disruptions, such as natural disasters, employee strikes, and other similar incidents, are infrequent. It can be challenging to allocate enough resources to address such maintenance events since it would significantly increase maintenance costs. Therefore, this study does not consider such events at this time. Nonetheless, future research can explore maintenance scheduling adjustments that arise from major disruptions.

2.2 Nomenclature

Before introducing the model, the symbols and notation are defined as follows.

Variables:

$\mathbf{y_{ij}^{m,d,s}}$: flow of arc (i, j) in the m,d,s^{th} layers (that is the mth maintenance subsection for the sth shifton thed^{th} day) in the maintenance scheduling network;

Parameters:

d : d^{th} day in a week;

e : e^{th} work order for preventive maintenance/corrective maintenance/ outsourced supporting maintenance/emergency maintenance. The information in the work order includes the subsection responsible, the destination site, the type of maintenance, the cost of maintenance and the penalty if unexecuted preventive maintenance;

m : m^{th} subsection, m= 1-20;

$MI^{m,d}$: minimum quantity of work orders that can be executed on the dth day by the mth subsectionin the maintenance scheduling network;

$MA^{m,d,s}$: maximum quantity of work orders that can be executed in the m,d,s^{th} layers in the maintenance

scheduling network.

$p_{ij}^{m,d,s}$: arc (i, j) cost in the m,d,sth layers in the maintenance scheduling network;

$q_{ij}^{m,d,s}$: upper bound of arc (i, j) for standby/collection in the m,d,sth layers in the maintenance scheduling network;

$r_i^{m,d,s}$: supply/demand for node i in the m,d,sth layers in the maintenance scheduling network. If $\mathbf{r_i^{m,d,s}}$is positive, node i represents a supply node. Otherwise, node i represents a demand node in the network if $\mathbf{r_i^{m,d,s}}$is negative;

s : sth shift, s=1-3 in this study;

$U_j^{d,s}$: maximum number of maintenance teams which can execute the maintenance in the sth shift on the dth day at node j;

Sets:

$\mathbf{A^{m,d,s}/N^{m,d,s}}$: set of all arcs/nodes in each m,d,sth layers in the maintenance scheduling network;

$\mathbf{A_e^{m,d,s}}$: set of all arcs for eth work order of preventive maintenance in the m,d,sth layers in the maintenance scheduling network;

$\mathbf{AH^{m,d,s}}$: set of all standby arcs and collection arcs in each m,d,sth layers in the maintenance scheduling network;

$\mathbf{B_e^{m,d,s}}$: set of all arcs for the eth work order for corrective maintenance within the time windows (from 11:00pm to 11:00pm the next day) in the m,d,sth layers in the maintenance scheduling network;

D : set of days;

$\mathbf{D_e}$: set of days in which the eth work order for maintenance can be executed;

E : set of work orders for preventive maintenance;

$\mathbf{E_m}$: set of maintenance subsections which can execute preventive maintenance;

F : set of work orders for corrective maintenance;

H : set of work orders for outsourced supporting maintenance;

INT : set of integers;

K : set of work orders for emergency maintenance;

M : set of all maintenance subsections;

$\mathbf{M_e}$: set of maintenance subsections that can execute the eth work order. $\mathbf{M_e}$ represents the set of responsible maintenance subsections for preventive, corrective, or supporting maintenance. In addition, there are three plants - the Electronic Engineering Plant, the Electronic Plant, and the Track and Civil Engineering Plant- which have a total of 20 maintenance subsections. If a failure occurs that affects the safety of operations or passenger services, the subsections of relevant plant will be responsible for carrying out emergency maintenance within the permitted time window;

$\mathbf{MD^{m,d,s}}$: set of demand nodes in the m,d,sth layers in the maintenance scheduling network;

$\mathbf{MS^{m,d,s}}$: set of supply nodes in the m,d,sth layers in the maintenance scheduling network;

$\mathbf{MT^{m,d,s}}$: set of transit nodes in the m,d,sth layers in the maintenance scheduling network;

N : set of sites；

$\mathbf{OS^{m,d,s}}$: set of outsourced supporting maintenance nodes in the m,d,sth layers in the maintenance scheduling network;

$\mathbf{Q_e^{m,d,s}}$: set of arcs for the eth work order for emergency maintenance within the permitted time window (2 hours) in the m,d,sthlayers in the maintenance scheduling network;

$\mathbf{R_j^{m,d,s}}$: set of all arcs directing to node j in the m,d,sth layers in the maintenance scheduling network;

S : set of shifts;

$\mathbf{S_e}$: set of shifts which include a maintenance team to execute the eth work order for emergency maintenance;

$\mathbf{Z_e^{m,d,s}}$: set of arcs represents the work orders for outsourced supporting maintenance in the mth subsection,dthday, and sth shift in the maintenance scheduling network. These work orders are only permitted to be executed during a specified time window of 8 hours per shift to avoid cross-shift operations. This time window is enforced as a constraint for the outsourced supporting teams, who typically work in cooperation with the on-duty maintenance staff.

2.3 Themodel

The model is formulated as follows:

$$MinZ = \sum_{m \in \boldsymbol{M}} \sum_{ij \in \boldsymbol{A^{m,d,s}}} (p_{ij}^{m,d,s} \times \boldsymbol{y_{ij}^{m,d,s}}). \quad (1)$$

s.t.

$$\sum_{j \in \boldsymbol{N^{m,d,s}}} (\boldsymbol{y_{ij}^{m,d,s}}) - \sum_{h \in \boldsymbol{N^{m,d,s}}} (\boldsymbol{y_{hi}^{m,d,s}}) = \begin{cases} \boldsymbol{r^{m,d,s}}, & \forall\, i \in \boldsymbol{MS^{m,d,s}} \\ -\boldsymbol{r^{m,d,s}}, & \forall\, i \in \boldsymbol{MD^{m,d,s}} \\ 0\,, & \forall\, i \in \boldsymbol{MT^{m,d,s}} \end{cases} \quad \forall s \in \boldsymbol{S}, \forall d \in \boldsymbol{D}, \forall m \in \boldsymbol{M} \quad (2)$$

$$\sum_{j \in \boldsymbol{OS^{m,d,s}}} \left(\boldsymbol{y_{ij}^{m,d,s}}\right) - \sum_{h \in \boldsymbol{OS^{m,d,s}}} \left(\boldsymbol{y_{hi}^{m,d,s}}\right) = \boldsymbol{0} \quad \forall\, i \in \boldsymbol{OS^{m,d,s}}, \forall s \in \boldsymbol{S}, \forall d \in \boldsymbol{D}, \forall m \in \boldsymbol{M} \quad (3)$$

$$\sum_{m \in \boldsymbol{M}} \sum_{ij \in \boldsymbol{R_j^{m,d,s}}} (\boldsymbol{y_{ij}^{m,d,s}}) \le U_j^{d,s}, \quad \forall j \in \bigcup_{\boldsymbol{m}} \boldsymbol{N^{m,d,s}}, \forall s \in \boldsymbol{S}, \forall d \in \boldsymbol{D} \quad (4)$$

$$\sum_{s \in \boldsymbol{S}} \sum_{ij \in \boldsymbol{B_e^{m,d,s}}} \boldsymbol{y_{ij}^{m,d,s}} = 1, \quad \forall m \in \boldsymbol{M_e}, \forall d \in \boldsymbol{D_e}, \forall e \in \boldsymbol{F} \quad (5)$$

$$\sum_{s \in \boldsymbol{S}} \sum_{ij \in \boldsymbol{Z_e^{m,d,s}}} \boldsymbol{y_{ij}^{m,d,s}} = 1, \quad \forall m \in \boldsymbol{M_e}, \forall d \in \boldsymbol{D_e}, \forall e \in \boldsymbol{H} \quad (6)$$

$$\sum_{m \in \boldsymbol{M_e}} \sum_{ij \in \boldsymbol{Q_e^{m,d,s}}} \boldsymbol{y_{ij}^{m,d,s}} = 1\,, \quad \forall s \in \boldsymbol{S_e}, \forall d \in \boldsymbol{D_e}, \forall e \in \boldsymbol{K} \quad (7)$$

$$\sum_{e \in \boldsymbol{E_m}} \sum_{ij \in \boldsymbol{A_e^{m,d,s}}} \boldsymbol{y_{ij}^{m,d,s}} \le MA^{m,d,s}\,, \quad \forall s \in \boldsymbol{S}, \forall d \in \boldsymbol{D}, \forall m \in \boldsymbol{M} \quad (8)$$

$$\sum_{s \in \boldsymbol{S}} \sum_{e \in \boldsymbol{E_m}} \sum_{ij \in \boldsymbol{A_e^{m,d,s}}} \mathbf{y_{ij}^{m,d,s}} \ge \mathrm{MI}^{\mathrm{m,d}}\,, \quad \forall \mathrm{d} \in \mathbf{D}, \forall \mathrm{m} \in \mathbf{M} \quad (9)$$

$$0 \le \mathbf{y_{ij}^{m,d,s}} \le \mathrm{q}_{\mathrm{ij}}^{\mathrm{m,d,s}}\,,\ \mathbf{y_{ij}^{m,d,s}} \in \mathbf{INT}\,, \quad \mathrm{ij} \in \mathbf{AH^{m,d,s}}, \forall \mathrm{s} \in \mathbf{S}, \forall \mathrm{d} \in \mathbf{D}, \forall \mathrm{m} \in \mathbf{M} \quad (10)$$

$$\mathbf{y_{ij}^{m,d,s}} \in \{0\,,\ 1\}, \quad \forall \mathrm{ij} \in \mathbf{A^{m,d,s}} \setminus \mathbf{AH^{m,d,s}}, \forall \mathrm{s} \in \mathbf{S}, \forall \mathrm{d} \in \mathbf{D}, \forall \mathrm{m} \in \mathbf{M}. \quad (11)$$

Equation (1) is to minimize the total maintenance cost. Equation (2) ensures the flow conservation of maintenance teams for every node in the time-space network. Equation (3) ensures flow conservation for the outsourced support teams for the outsourced supporting maintenance related nodes in the maintenance time-space network. Equation (4) denotes that the maximum number of teams permitted to execute maintenance work at the same time in one site. Equation (5) guarantees that each predicted work order for corrective maintenance is executed by the responsible maintenance subsection on each day. Equation (6) guarantees that each predicted work order for outsourced supporting maintenance is executed by the responsible contractor on each day. Equation (7) guarantees that each predicted work order for emergency maintenance is executed by subsections of the responsible maintenance plant in each shift on each day. Equation (8) limits the maximum number of work orders for preventive maintenance that can be executed by the responsible maintenance subsection in each shift on each day. Equation (9) indicates that the sum of work orders for preventive maintenance executed by each maintenance subsection on each day must be not less than or equal to the total amount for one week. Equation (10) indicates that all standby arcs and collection arcs are integers and within their bounds. Equation (11) ensures that all arc flows for preventive maintenance, corrective maintenance, outsourced supporting maintenance and emergency maintenance in the maintenance scheduling network are binary. Themodel can be optimally solved using the mathematical programming solver CPLEX.

III. CASE STUDY

To preliminarily evaluate the model, we conducted a case study adopting relevant data from a domestic metropolitan railway companyin Taiwan (Company A). All the tests were performed on a desktop with a Core i5-7200 2.5 GHz CPU with 12GB of RAM, coupled with CPLEX.

The company in Taiwan comprised 20 maintenance subsections that belonged to 9 sections across 3 plants. We obtained a real history record of 635 maintenance work orders from Company A for one week. Table 1 summarizes the types and quantities of maintenance work orders, providing a more detailed breakdown of the data.

Preventive maintenance	337
Corrective maintenance	243
Emergency maintenance	30
Outsourced supporting maintenance	25
Total work orders	635

Table 1. The composition of work orders.

The other relevant information, including maintenance type, necessary time and cost, travel costs between sites, and available on-duty maintenance teams, is provided by Company A.

In the case study, we used the maintenance scheduling model to schedule 635 maintenance work orders, with the aim of minimizing overall maintenance cost. The results in Table 2 showed that the model consisted of 1,214,350 variables and 1,415,343 constraints, including 10,409 side constraints, and 190,584 constraints ensuring flow conservation at each node, as well as 1,214,350 constraints ensuring the bounds of the arc flows in the model.

Our findings demonstrated the potential usefulness of the model in maintenance scheduling for metropolitan railways. Based on the test results, it is worth noting that solving the model using CPLEX took a long time, so further development of a heuristic algorithm may be necessary in the future.

Number of Standby arcs	11760
Number of collection arcs	188160
Number of non-completed PM	337
Number of maintenance arcs	1014093
Number of variables	1214350
Number of conservation constraints	190584
Number of side constraints	10409
Number of bin constraints	1014430
Convergence GAP (%)	0.98%
Total computation time (seconds)	86703.03
Objective (NT dollars)	$3,722,900

Table 2. Test results.

IV. CONCLUSIONS

In this study, our aim was to develop a maintenance scheduling model for railway facilities that would minimize overall maintenance costs using a combination of mathematical programming and time-space network techniques. The model specifically focused on the maintenance of railway infrastructure, excluding rolling stock and depot equipment, as these activities were addressed separately. To demonstrate the usefulness of the model, we conducted a case study. The preliminary test results indicated that our model was potentially useful and developing a heuristic algorithm would help improve the efficiency of solving the model.

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