



THE MANPOWER SUPPLY PLANNING AND SHIFT SETTING FOR MASS RAPID TRANSIT CARRIAGE MAINTENANCE IN SHORT-TERM OPERATIONS

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THE MANPOWER SUPPLY PLANNING AND SHIFT SETTING FOR MASS RAPID TRANSIT CARRIAGE MAINTENANCE IN SHORT-TERM OPERATIONS

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Key words: carriage maintenance, manpower supply, mixed integer program, flexible strategy.

ABSTRACT

An effective carriage maintenance plan cannot only reduce the mass rapid transit system operating costs, but is also directly related to its safety and schedule punctuality. Traditionally, the arrangement of the carriage maintenance manpower supply has been based on staff experience, and has been performed manually following simple rules. This is not only time-consuming but often ineffective. Therefore, in this research, we incorporate flexible management strategies, different combinations of principles, and the related operating constraints, to develop a basic carriage maintenance manpower supply plan model. Furthermore, we construct an integrated model by modifying the basic model, which can help an MRT plant more effectively manage its maintenance manpower. To evaluate the models in practice, a case study using real operation data from a Taiwan MRT maintenance facility is performed, with the assistance of C computer programs and a mathematical programming solver. The preliminary results are good, showing that the models could be useful for planning short-term carriage maintenance manpower supply.

I. INTRODUCTION

An effective carriage maintenance plan cannot only reduce the mass rapid transit system (MRT) operating costs, but is also directly related to its safety and schedule punctuality. A good carriage maintenance manpower supply plan not only meets all the safety requirements but will also help better manage maintenance resources and improve service quality. As a result, it is a very important issue to an MRT in determining a good carriage maintenance manpower supply plan.

Generally, the carriage maintenance manpower supply plans

are classified into short- and long-terms ones. The short-term one, which involves the current MRT's operations, is usually performed before the beginning of the next period (a period contains a couple of months). On the other hand, the long-term one is usually performed at the beginning of the year (or several years in advance), according to the predicted carriage maintenance/manpower demands based on historical information. The constraints in these two types of plans are different. In particular, the carriage maintenance manpower available for a short-term plan is constrained by current carriage maintenance manpower resource. How to set a good carriage maintenance manpower supply plan for short-term operations is more difficult than for long-term ones. Therefore, in this research we focus on a short-term carriage maintenance manpower supply plan. Using a Taiwan MRT maintenance facility (called X MRT hereinafter) as an example, we introduce the procedure for determining short-term carriage maintenance manpower supply plan in practice.

In the X MRT, two departments are responsible for carriage maintenance, which are the preventive maintenance department (PMD) and the breakdown maintenance department (BMD). The PMD has to deal with the preventive carriage maintenance, such as daily and monthly checks; while the BMD is responsible for maintenance work after carriage breakdown occurs. The demand for PMD is a fixed demand, but that for BMD may fluctuate from time to time, depending on unexpected events. In current practices, an average demand is estimated and is used for planning. Furthermore, these two departments normally use 3 shifts and 2 shifts (although sometimes from 2 to 6 shifts are occasionally used). In addition, a flexible working hour strategy allows X MRT to hire both full-time and half-time employees, although they usually have full-time employees, most often divided into 6 people to a team/crew (occasionally from 3 to 6 people teams are used). In theory, more shifts would increase the degrees of freedom in scheduling, thus conserving manpower, but would of course result in a more complicated manpower supply plan. Therefore, for ease of scheduling, X MRT simplifies its maintenance manpower supply plan to have 3 PMD shifts and 2 BMD shifts.

In current practices, X MRT depends on staff experience in establishing the carriage manpower supply plan, which is outlined as follows. The planning procedure for carriage man-

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power supply typically consists of three stages: (1) the initial carriage maintenance demand estimation, (2) MRT maintenance manpower supply planning, and (3) crew assignment. Of the three stages, the first stage is typically simple, a statistical work. The second stage is complicated and its results serve as the basis of the third stage. In other words, crew assignment is handled after the manpower supply problem is solved. Not only does a good MRT maintenance manpower supply plan make crew assignment easier, but also reduces the MRT maintenance manpower crew cost. However, X MRT currently utilizes a trial-and-error experience-based method with a projected demand for carriage manpower supply plan, without optimization from a system perspective. Such a trial-and-error method is neither efficient nor effective. Therefore, this research focuses on planning short-term carriage maintenance manpower supply planning, which corresponds to the second stage of the overall planning procedure mentioned above. To help the reader understand the background, we now discuss some of the past research on personnel scheduling and flexible management strategies that are related to ours.

Much research has already been devoted to personnel scheduling problems. For examples of recent research, see Brusco and Johns [5], Lau [10], Narasimhan [11], Langerman and Ehlers [9], Caprara *et al.* [7], Beaumont [3], Brusco [6], Alfares [1], Higgins [8], Teodorović and Lučić [12], Aykin [2], Yan and Tu [13], Yan *et al.* [16], Yan *et al.* [14], and Yan *et al.* [15]. However, their problem characteristics are not the same as those needed for a carriage maintenance manpower supply plan, meaning that the above models or solutions are not applicable or can not be directly applied to our problem. In addition, the flexible management strategies have been widely recognized in the industry and the results indicate that flexible management strategies can increase the different degrees of freedom in the schedule, thus conserving manpower (Blyton and Morris, [4]). The flexible management strategy, however, has not yet been applied to MRT carriage maintenance manpower supply plans. As a result, we did not find any that addressed MRT carriage maintenance manpower supply planning problems, with flexible management strategies in particular.

An effective combination of shift starting times, the number of shifts, and the number of crews is the key to a successful carriage maintenance manpower supply plan. Therefore, in this research, a basic carriage maintenance manpower supply plan model (for convenience, hereinafter called the BM), incorporating flexible management strategies, different combinations of principles, and the related operating constraints, is developed. Moreover, an integrated model (for convenience, hereinafter called the IM) is further developed by modifying the BM according to the similar characteristics of the PMD and the BMD, which can help X MRT plant more effectively manage its maintenance manpower. The models are formulated as mixed integer linear programs and are solved using a mathematical programming solver. Finally, to evaluate how the models perform in practice, a case study using real operation data from X MRT maintenance facility is performed, with the assistance of C

computer programs and a mathematical programming solver.

The scope of this research is confined to the subject of MRT carriage maintenance manpower supply and shift setting, given the projected manpower demands, the upper/lower bound of the shift starting times, the working hours for each shift, the team members for a work type, and other related cost data. In addition, since the X MRT timetable is rotated weekly, the planning cycle is one week (seven days). For the planning week, shift starting times have to be the same every day of the week. It should be mentioned that, in practice, the salary structure varies according to personnel experience, length of employment, education and other factors. It would be too complicated to model minimum salary expense as an objective function in the planning stage, so for ease of modeling, this study focuses on the minimization of the maintenance manpower supply in man-hours.

The remainder of the paper is organized as follows. We first describe the problem, and then formulate the models. Thereafter, we perform numerical tests to evaluate the performance of the models. Finally we give some conclusions.

II. THE MODELS

In this section, the modeling concept is first discussed according to the X MRT's current practices. Then a basic model (BM) is formulated incorporating three flexible management strategies. According to the similar characteristics of the PMD and the BMD and the use of excess maintenance manpower between the two departments, the BM is modified to further develop an integrated model (IM).

1. Modeling Concept

The study focuses on modeling a complicated short-term carriage maintenance manpower supply plan. According to the X MRT operations, PMD demand is given and fixed in advance. The BMD demand is given by an expectedly average demand. These demands typically vary in a week. Sometimes in off-peak hours there may even be no demand which makes flexible strategies a good idea for improving efficiency of X MRT maintenance manpower planning. Taking into consideration X MRT practices, three flexible strategies can be proposed based on numerical and temporal concepts: flexible shifts, flexible team members, and flexible working hours. The flexible shift strategy allows an employer to choose the preferred number of shift starting times per day and the shift starting times. These need not be limited to the conventional three fixed shifts (i.e., 0:00-8:00, 8:00-16:00, and 16:00-0:00) for the PMD nor the two fixed shifts for the BMD (i.e., 8:00-16:00, and 16:00-0:00) currently utilized by X MRT. In the flexible team member strategy the number of team members can be adjusted in response to changes (from 3 to 6 in this research) in demand in different time slots. The flexible working hour strategy allows X MRT to hire both full-time and half-time employees. Two types of flexibility are introduced in our model: full-time (eight hours) shifts and half-time (four hours) shifts.

Traditionally, the planner only considers matching its main-

tenance manpower supply to the demand, neglecting the use of excess maintenance manpower. However, in actual practice, surplus maintenance manpower may be shifted to other departments, to further enhance efficiency. In addition, if the PMD and the expected BMD demand for continuous time slots fluctuate drastically (e.g., at the boundaries between peak and off-peak periods), then supplying too much maintenance manpower to meet the highest demand would result in surplus manpower and a waste of human resources, though they can be of use in some ways. One way to deal with drastic fluctuations in maintenance manpower demands in continuous time slots is to temporarily supplement manpower from another maintenance department or off-duty personnel, even if the unit man-hour cost is normally higher than the regular unit man-hour cost.

However, to determine what trade-off between surplus and insufficient maintenance manpower is most appropriate for each slot for each work type is too complicated to be solved without a systematic model. We propose two systematic models that incorporate three flexible strategies and two combinations of manpower supply principles in order to provide effective MRT maintenance manpower supply plans. The plans are not only responsive to wide variations in maintenance manpower demand but can also help the X MRT maintenance facility manage its manpower resources more effectively, and consequently reduce its operating cost.

2. BM

Incorporating flexible management strategies, different combinations of principles, and the related operating constraints, the basic model (BM) is formulated. The notations for parameters and variables used in the model formulation are listed below.

Parameters:

- D : the set of days in a week. Since our planning period is one week (seven days), $D \equiv \{0: \text{Sunday}, 1: \text{Monday}, 2: \text{Tuesday}, 3: \text{Wednesday}, 4: \text{Thursday}, 5: \text{Friday}, 6: \text{Saturday}\}$.
- d : the d^{th} day in a week; $d \in D$.
- S : the set of shift starting times in one day. The length of a time slot is set to be one hour. Since there are 24 hours in a day; $S \equiv \{0, 1, 2, 3, 4, 5, \dots, 23\}$.
- t : the t^{th} time slot in a day; $t \in S$.
- s : the s^{th} shift starting time; $s \in S$. A shift starting time indicates when the shifts (of different types) start. According to real practices, the shift starting time is the same each day of the week. If an MRT garage does not prefer to specify the starting times (for example, to prevent the yielding of shifts that start too close together), then these shift starting times can be removed from S . On the contrary, if the maximum number of shift starting times is constrained due to practical concerns, then a

constraint should be imposed.

- P : the set of different team sizes (i.e., different numbers of crew members).
- p : type p maintenance team; $p \in P$.
- m_p : the number of persons in a type p maintenance team.
- W : the set of different types of work, to differentiate between full-time and part-time employees.
- w : type w work; $w \in W$.
- h_w : the working hours for type w work.
- rc_{PMD}, rc_{BMD} : the regular manpower cost per man-hour for the PMD and for the BMD, respectively. In short term operations, since the crew salary (the main part) has already been paid, rc_{PMD} and rc_{BMD} are typically not large.
- ec_{PMD}, ec_{BMD} : the value per surplus man-hour for manpower supply exceeding demand for the PMD and for the BMD, respectively, which could be used by the other department, and is thus in the form of a negative cost. In practice, $|ec_{PMD}|$ is smaller than rc_{PMD} , because ec_{PMD} is a derivative value. Similarly, $|ec_{BMD}|$ is smaller than rc_{BMD} , because ec_{BMD} is a derivative value. Note that if the excess manpower is not well planned in advance in short-term operations, then $|ec_{PMD}|$ and $|ec_{BMD}|$ are small.
- ic_{PMD}, ic_{BMD} : the cost per temporary man-hour supply for insufficient manpower for the PMD and for the BMD, respectively. Insufficient manpower may be supplemented temporarily from the other maintenance department or be trainees without qualifications. In practice, ic_{PMD} and ic_{BMD} are greater than rc_{PMD} and rc_{BMD} , respectively, in short-term operations.
- u_{PMD}, u_{BMD} : the upper bound of the total number of shifts in one day for both the PMD and the BMD.
- pd_{dt} : the PMD maintenance manpower demand in time slot t on day d . It is measured as the number of persons.
- bd_{dt} : the BMD maintenance manpower demand in time slot t on day d . It is measured as the number of persons.
- ps_{dt} : the upper bound of the PMD manpower which can be supplied in time slot t on day d .
- bs_{dt} : the upper bound of the BMD manpower which can be supplied in time slot t on day d .
- M : a very large value for ease of modeling.

H_{dtw} : the set of all shifts supplying type w work in time slot t on day d .

The purpose of H_{dtw} is to represent the relationship between the manpower supply of shifts for different work types and the working time slots. Using H_{dtw} , we can identify all the shifts of type w work that will be on duty in time slot t on day d .

Variables:

v_{dspw}^{PMD} : the number of type p teams for type w work for PMD starting at shift s on day d .

v_{dspw}^{BMD} : the number of type p teams for type w work for BMD starting at shift s on day d .

x_s^{PMD} : $x_s^{PMD} = 1$ if there are shifts for PMD starting at s , and 0 otherwise.

x_s^{BMD} : $x_s^{BMD} = 1$ if there are shifts for BMD starting at s , and 0 otherwise.

$e_{dt}^{PMD}, i_{dt}^{PMD}$: the excess manpower and insufficient manpower (in persons) for PMD in time slot t on day d .

$e_{dt}^{BMD}, i_{dt}^{BMD}$: the excess manpower and insufficient manpower (in persons) for BMD in time slot t on day d .

The BM is formulated as a mixed integer linear program as follows:

$$\begin{aligned} \text{Min } z = & rc_{PMD} \times \sum_{d \in D} \sum_{s \in S} \sum_{p \in P} \sum_{w \in W} h_w \times m_p \times v_{dspw}^{PMD} \\ & + rc_{BMD} \times \sum_{d \in D} \sum_{s \in S} \sum_{p \in P} \sum_{w \in W} h_w \times m_p \times v_{dspw}^{BMD} \\ & + ec_{PMD} \times \sum_{d \in D} \sum_{t \in S} e_{dt}^{PMD} + ic_{PMD} \times \sum_{d \in D} \sum_{t \in S} i_{dt}^{PMD} \\ & + ec_{BMD} \times \sum_{d \in D} \sum_{t \in S} e_{dt}^{BMD} + ic_{BMD} \times \sum_{d \in D} \sum_{t \in S} i_{dt}^{BMD} \end{aligned} \quad (1)$$

ST

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{PMD} - e_{dt}^{PMD} + i_{dt}^{PMD} = pd_{dt}, \forall d \in D, \forall t \in S \quad (2)$$

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{BMD} - e_{dt}^{BMD} + i_{dt}^{BMD} = bd_{dt}, \forall d \in D, \forall t \in S \quad (3)$$

$$\sum_{s \in S} x_s^{PMD} \leq u_{PMD} \quad (4)$$

$$\sum_{s \in S} x_s^{BMD} \leq u_{BMD} \quad (5)$$

$$\sum_{d \in D} \sum_{p \in P} \sum_{w \in W} v_{dspw}^{PMD} \leq Mx_s^{PMD}, \forall s \in S \quad (6)$$

$$\sum_{d \in D} \sum_{p \in P} \sum_{w \in W} v_{dspw}^{BMD} \leq Mx_s^{BMD}, \forall s \in S \quad (7)$$

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{PMD} \leq ps_{dt}, \forall d \in D, \forall t \in S \quad (8)$$

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{BMD} \leq bs_{dt}, \forall d \in D, \forall t \in S \quad (9)$$

$$x_s^{PMD} = 0 \text{ or } 1, \forall s \in S \quad (10)$$

$$x_s^{BMD} = 0 \text{ or } 1, \forall s \in S \quad (11)$$

$$v_{dspw}^{PMD} \geq 0 \ \& \ v_{dspw}^{PMD} \in I, \forall d \in D, \forall s \in S, \forall p \in P, \forall w \in W \quad (12)$$

$$v_{dspw}^{BMD} \geq 0 \ \& \ v_{dspw}^{BMD} \in I, \forall d \in D, \forall s \in S, \forall p \in P, \forall w \in W \quad (13)$$

$$e_{dt}^{PMD} \geq 0 \ \& \ i_{dt}^{PMD} \geq 0, \forall d \in D, \forall t \in S \quad (14)$$

$$e_{dt}^{BMD} \geq 0 \ \& \ i_{dt}^{BMD} \geq 0, \forall d \in D, \forall t \in S \quad (15)$$

Equation (1) is the objective function that minimizes the total system cost that includes the regular manpower cost for the two departments, the negative surplus value of excess manpower, and the temporary manpower supply cost for insufficient manpower. It should be mentioned that the cost resulted from different numbers of shift starting times is not significant in the current X MRT operations and therefore can be neglected. If this cost is significant in other applications, then the objective function can be modified and the cost $\sum_{s \in S} (a_s^{PMD} x_s^{PMD} + b_s^{BMD} x_s^{BMD})$

added to the objective function, to reflect this concern, where a_s^{PMD} and b_s^{BMD} denote the costs for the PMD and the BMD, respectively, for setting the shift starting time s . Equations (2) and (3) state that for the PMD and for the BMD, respectively, the assigned crew members, subtracting excess manpower and adding temporary supplied manpower, must be able to meet the manpower demands in every time slot during their shift. Equations (4) and (5) constrain the maximum number of shift starting times in each day for the PMD and the BMD, respectively. Note that if the least number of shift starting times needs to be considered in other applications, then Equations (4) and (5) can be modified to become $l_{PMD} \leq \sum_{s \in S} x_s^{PMD} \leq u_{PMD}$ and

$l_{BMD} \leq \sum_{s \in S} x_s^{BMD} \leq u_{BMD}$, respectively, where l_{PMD} and l_{BMD} de-

note the least number of shift starting times for the PMD and the BMD, respectively. Equations (6) and (7) ensure that PMD and BMD maintenance teams are assigned to a shift only when that shift exists. Equations (8) and (9) ensure that the amount of PMD and BMD manpower in every time slot during the shift does not exceed the available amount of manpower. Equations (10), (11), (12) and (13) are integer constraints for the variables. Equations (14) and (15) are variable nonnegativity constraints. Note that $e_{dt}^{PMD}, i_{dt}^{PMD}, e_{dt}^{BMD}$ and i_{dt}^{BMD} are not constrained to be integers. However, due to constraints (2) and (3) and the integrality of pd_{dt} and bd_{dt} , they are naturally integers.

Given the required demand and the maximum supply of manpower for each time slot of each day, the work types, the feasible range of shifts and the related cost, the model determines the best set of shifts, each with a number of work types, and the excess or temporary supplied manpower in each time

slot, in each day of the week. The model is solved using the mathematical programming solver, CPLEX.

3. IM

According to the similar characteristics of the PMD and the BMD in the current X MRT practices, we further construct an integrated model, IM. With the IM not only can we establish these two departments' manpower supply plan separately, but we can also allow them to support each other, thereby increasing the flexibility of personnel arrangement. However, there are some differences between the PMD and the BMD, in terms of the level of expertise and the ability. Therefore, to conform to real practices, a manpower reduction coefficient should be incorporated into the IM. In addition, the amount of manpower available to support the other department should not exceed the maximum available manpower. More effective use of manpower resources leads to reduction in the IM costs. Additional parameters/variables for the IM are defined below.

- as_{dt}^{PMD} : the maximum number of PMD manpower units available for supporting the BMD in time slot t on day d .
- as_{dt}^{BMD} : the maximum number of BMD manpower units available for supporting the PMD in time slot t on day d .
- k_1 : the reduction coefficient for using the BMD manpower to support the PMD demand. The value is between 0 and 1.
- k_2 : the reduction coefficient for using the PMD manpower to support the BMD demand. Similar to k_1 , the value is between 0 and 1.

The IM is formulated as a mixed integer linear program as follows:

$$\begin{aligned}
 \text{Min } z = & rc_{PMD} \times \sum_{d \in D} \sum_{s \in S} \sum_{p \in P} \sum_{w \in W} h_w \times m_p \times v_{dspw}^{PMD} \\
 & + rc_{BMD} \times \sum_{d \in D} \sum_{s \in S} \sum_{p \in P} \sum_{w \in W} h_w \times m_p \times v_{dspw}^{BMD} \\
 & + ec_{PMD} \times \sum_{d \in D} \sum_{t \in S} e_{dt}^{PMD} + ic_{PMD} \times \sum_{d \in D} \sum_{t \in S} i_{dt}^{PMD} \\
 & + ec_{BMD} \times \sum_{d \in D} \sum_{t \in S} e_{dt}^{BMD} + ic_{BMD} \times \sum_{d \in D} \sum_{t \in S} i_{dt}^{BMD}
 \end{aligned} \tag{1}$$

ST

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{PMD} - as_{dt}^{PMD} + k_1 \times as_{dt}^{BMD} - e_{dt}^{PMD} + i_{dt}^{PMD} = pd_{dt}, \tag{16}$$

$\forall d \in D, \forall t \in S$

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{BMD} - as_{dt}^{BMD} + k_2 \times as_{dt}^{PMD} - e_{dt}^{BMD} + i_{dt}^{BMD} = bd_{dt}, \tag{17}$$

$\forall d \in D, \forall t \in S$

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{PMD} \geq as_{dt}^{PMD}, \forall d \in D, \forall t \in S \tag{18}$$

$$\sum_{p \in P} \sum_{w \in W} \sum_{s \in H_{dtw}} m_p \times v_{dspw}^{BMD} \geq as_{dt}^{BMD}, \forall d \in D, \forall t \in S \tag{19}$$

$$as_{dt}^{PMD} \geq 0 \ \& \ as_{dt}^{PMD} \in I, \forall d \in D, \forall t \in S \tag{20}$$

$$as_{dt}^{BMD} \geq 0 \ \& \ as_{dt}^{BMD} \in I, \forall d \in D, \forall t \in S \tag{21}$$

and equations (4) to (15).

To save space, we only introduce below those IM equations which are different from the BM ones. Equation (16) states that the assigned crew members, minus the manpower for supporting BMD, plus manpower supplied from PMD, that is subtracting excess manpower and adding temporary supplied manpower, must be enough to meet the manpower demands in every time slot during this shift. Similar to Equation (16), equation (17) states that the assigned crew members, minus the manpower for supporting PMD, plus manpower supplied from BMD, that is subtracting excess manpower and adding temporary supplied manpower, must be enough to meet the manpower demands in every time slot during the shift. Equations (18) and (19) indicate that the total number of PMD and BMD manpower units in every time slot has to be enough to satisfy the largest amount required. Equations (20) and (21) are constrained to be integer variables. Given the required demand and the maximum supply of manpower for each time slot of each day, the work types, the feasible range of shifts and the related cost, the model determines the best set of shifts, each with a number of work types, the excess or temporary supplied manpower in each time slot and the supporting manpower in each time slot, in each day of the week. The model is solved using the mathematical programming solver, CPLEX.

III. NUMERICAL TESTS

To test how well the models may be applied in the real world, numerical tests mainly using operating data from X MRT maintenance facility are performed. The assistance of C computer language and the mathematical programming solver, CPLEX 8.1, are used to build the model and to solve the problems. The tests are performed on a Pentium 4 – 2G with 1Gb of RAM in the environment of Microsoft Windows XP.

1. Data Analysis

The maintenance demands of the X MRT's two maintenance departments during September of 2006 are used as our test data. The inputs, such as the upper bound of maintenance manpower supply in each time slot, the working hours of different work types, and the upper/lower bound of the shift starting times, are primarily adopted from actual operating data. According to the real practices, two different work types are set to make for a more flexible strategy (full-time and half-time). In addition, the normal number of shift starting times used in X MRT is three, although as many as six shift starting times may occasionally be used. Therefore, the feasible range is set from three to six shift starting times. Furthermore, the team size used in X MRT is six, although sometimes from three to six people teams are occasionally used. Therefore, the team size range is set from three to six people teams. The three cost parameter values, which are relative to each other, for the BM and the IM are as follows:

Table 1. Test results.

| | TAEM | | BM | | IM | |
|-----------------------------------|----------|---------|----------------|----------|----------------|----------|
| | PMD | BMD | PMD | BMD | PMD | BMD |
| OBJ (NT\$) | 22080 | | 21040 | | 21030 | |
| Computation time (seconds) | NA | | 1.31 | | 72.38 | |
| Required manpower (man-hours) | 866 | 1016.81 | 866 | 1016.81 | 866 | 1016.81 |
| Supply demand (man-hours) | 1056 | 1152 | 996 | 1108 | 1004 | 1089 |
| Excess manpower (man-hours) | 190* | 131* | 130 | 87 | 135.2 | 80.6 |
| Insufficient manpower (man-hours) | 0** | 0** | 0 | 0 | 0.4 | 0 |
| Supporting manpower (man-hours) | 0** | 0** | 0 | 0 | 22 | 12 |
| Number of shifts | 3 | 2 | 5 | 3 | 5 | 3 |
| Shift starting times | 09,10,23 | 07,15 | 02,03,09,10,23 | 07,11,15 | 00,02,09,10,23 | 07,11,15 |
| | | | | | 3 | 5 |

*The excess manpower for the PMD and the BMD for TAEM is externally calculated to be 190 and 131, respectively.

**The insufficient and the supporting manpower for the PMD and the BMD for TAEM are both 0 by definition.

The regular maintenance manpower cost per man-hour (rc_{PMD}, rc_{BMD}) is set to be 10. The value per surplus man-hour for maintenance manpower supply exceeding demand (ec_{PMD}, ec_{BMD}) is set to be zero, because X MRT does not consider the use of excess maintenance manpower in their short-term manpower supply plan. Since it is not easy to import temporary maintenance manpower from the other maintenance department or from outside the company in short-term operations, the cost per temporary man-hour supply for insufficient man-power (ic_{PMD}, ic_{BMD}) is set to be 250, as the closest reflection of real practice. Note that the three cost values are adjustable to meet the requirements of other MRTs.

Except for the above setting, in the IM model mutual support is taken into account to increase the flexibility of personnel arrangement. However, there are some differences between the PMD and the BMD, such as the level of expertise and the training of maintenance personnel. Therefore, to conform to real practices, a manpower reduction coefficient is considered in the IM. The level of expertise and the training of the BMD maintenance personnel are better than those of the PMD personnel. Therefore, we set the manpower reduction coefficient for the PMD (k_1) to be 0.9 and that of the BMD (k_2) to be 0.8. The two reduction coefficients are adjustable to meet other MRTs' operating requirements.

2. Test Results

Table 1 shows the test results. Note that to preliminarily evaluate the proposed models, the results are compared to those obtained using the current X MRT trial-and-error experience-based method (denoted as TAEM). As shown in Table 1, OBJ represents the system cost for the optimal solution obtained by CPLEX.

The IM yields the best solution, with an objective value of 21030. The BM performs slightly worse, with an objective value of 21040. The TAEM performed the worst, with an objective value of 22080. The results show that the two models outperformed the current trial-and-error method by a reduced cost of at least 4.94% ($= (22080 - 21040) / 21040$). Moreover, for

the BM, the excess and insufficient manpower for the PMD are 130 and 0 man-hours, respectively, while the excess and insufficient manpower for the BMD are 87 and 0 man-hours, respectively. For the IM, the excess and insufficient manpower for the PMD are 135.2 and 0.4 man-hours, respectively, while the excess and insufficient manpower for the BMD are 80.6 and 0 man-hours, respectively. From the above results it can be seen that the IM allowed for mutual support between these two departments to compensate for insufficient manpower. More specifically, by suitably trading off the excess and insufficient manpower for each slot of every work type and allowing the two departments to support each other mutually, the IM could help manage manpower more effectively than the BM.

For the number of shifts, we vary the number of shifts from 3 to 6, with starting times that could be any time slot in a day for the two models. In theory, more shifts would increase the degrees of freedom in scheduling. However, as shown in Table 1, all the models do not use the upper bound of the shift starting times. The reason is that there is no demand in some time slots in a day for the PMD and the BMD. For the computation times, they are very efficient, 1.31 seconds for the BM and 72.38 seconds for the IM.

From the test results, both the BM and the IM could improve over the current manual trial-and-error method. The IM was better than the BM in terms of flexibility. In summary, both the BM and the IM are efficient and effective for X MRT carriage maintenance manpower supply planning and shift setting in short-term operations.

IV. CONCLUSION

This study incorporates flexible management strategies, different combinations of principles, and the related operating constraints to develop a basic carriage maintenance manpower supply plan model (the BM). By suitably modifying the BM, an integrated model (the IM) is further developed. The models are formulated as mixed integer linear programs that are solved using a mathematical programming solver. A case study util-

izing real operating data from a Taiwan MRT is conducted to preliminarily evaluate the models and the solution algorithm in the real world. The results show that both the BM and the IM are an improvement over the trial-and-error method used in actual operations. Moreover, the IM is better than the BM in terms of flexibility. In summary, both the BM and the IM are efficient and effective for the MRT carriage maintenance manpower supply planning and shift setting in short-term operations.

Although the preliminary test results show that the models are potentially useful for manpower supply planning and shift setting, especially for the Taiwan MRT's operations, more tests or case studies should be conducted, so that users may grasp their limitations, before putting them to practical use. The models and the case study should all be useful references for the MRT when determining the most optimal short-term maintenance manpower schedule. Finally, in actual operations, some of the model parameters, such as manpower demands for BMD, are stochastic. How to modify the deterministic models to become mixed deterministic and stochastic models for a closer match of actual operations could also be a topic of future research.

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