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Transportation Research Part A 38 (2004) 615–642
TRANSPORTATION RESEARCH PART A
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Airline short-term maintenance manpower supply planning

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Received 24 July 2003; received in revised form 3 March 2004; accepted 26 March 2004

Abstract

It is essential that airlines efficiently perform aircraft maintenance in order to ensure aviation safety and schedule punctuality. Traditionally, the arrangement of the 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. In this research we consider technicians with multiple types of aircraft maintenance certificates incorporated with three flexible management strategies and the related operating constraints to develop a mathematical programming model. With suitable modifications, eight different flexible strategic models, associated with different strategy combinations, can be generated to help an airline effectively manage its maintenance manpower supply. The models are formulated as mixed integer programs. Because the problem sizes of the proposed models are expected to be huge in real applications, we have developed a solution algorithm to efficiently solve the problems. We employed the mathematical programming solver, CPLEX, to reach a solution for all the problems. Finally, to evaluate the models and solution algorithm developed in the research, we performed a case study using the operating data from a leading Taiwan airline. The preliminary results indicate that the proposed models, and the solution algorithm, are both efficient and effective.

Keywords: Maintenance manpower supply; Certificates; Management strategy; Mixed integer program

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0965-8564/$ - see front matter
doi:10.1016/j.tra.2004.03.005

1. Introduction

Airline crew costs involve a large investment, which is usually only second to the fuel costs among all airline operating costs, hence, airlines are continually seeking better ways to efficiently allocate their crew resources. Of all the airline crew and staff scheduling problems, aircraft maintenance crew scheduling cannot only reduce the operating costs, but is also directly related to aviation safety issues, which cannot be compromised in actual operations. A good maintenance manpower supply plan has to meet all the safety requirements as well as allow flight departures and arrivals to remain punctual. Both are critical to airline operations. Therefore, maintenance manpower scheduling is a very important issue to airlines.

Aviation safety is carefully regulated and it is mandatory that aircraft maintenance be performed according to these regulations. Such maintenance is complicated and requires many skilled technicians and specialized instruments. Therefore, maintenance work is usually separated into three different types, short-term, mid-term, and long-term. The short-term maintenance plan, which is also called short-term layover maintenance, is usually performed at the airport gates. The mid-term maintenance plan requires the performance of more checks and related jobs. For example, level A and level B maintenance checks are both included in the mid-term maintenance plan. It usually takes one or more days to finish all the jobs, and the aircraft needs to stay at the parking ramp while these tasks are performed. The long-term maintenance plan is the most sophisticated and requires detailed checks and related maintenance throughout the aircraft. Level C and level D maintenance checks are usually classified as long-term maintenance. The long-term plan usually takes 10 days or more and is usually performed at an airline's base airport. The different levels of maintenance require different professionals, different training, different certification, and different instruments. Therefore, the maintenance crew is usually separated into different groups, which are responsible for specific maintenance plans and tasks. For example, the short-term plan group focuses on layover maintenance tasks and technicians receive training for this type of work. For one leading Taiwan airline, unless they are really short of maintenance manpower, short-term plan teams are not assigned to perform long-term maintenance, since the training and the certificate types are different. Hence, the schedules for the different types of maintenance must usually be formulated separately. This study focuses on the airline maintenance manpower supply planning for the short-term layover maintenance. We start by introducing a short-term layover maintenance plan and a procedure for determining manpower schedules.

Short-term layover maintenance can usually be performed at the gate in about 1 or 2 h on average. The maintenance tasks are performed before departure and/or after arrival, therefore, timetable and time constraints have to be met, otherwise, flight delays (as well as extra operation costs) could be incurred. In general, short-term layover maintenance includes three types of jobs, preflight checks, transit checks, and daily checks. The preflight check is a regular procedure performed prior to each take-off. It has to be finished by the scheduled departure time. A transit check is required between every two connected flights serviced by the same airplane. A daily check is executed when an aircraft stays overnight at an airport. Since the three types of checks necessitate different tasks, their working-hour and man-hour requirements are different. Also, tasks may vary for different aircraft types. This means that maintenance manpower demands must be estimated in terms of the different aircraft types and their respective maintenance tasks. One important feature of the airline industry is the maintenance certification system, which requires that maintenance personnel have a particular type of certificate in order to maintain a particular type of aircraft. This is a strictly enforced regulation with zero tolerance. A maintenance crew can only work on an aircraft for which they have a certificate. Some crew members may have several certificates for different types of aircraft, while some only have one type of certificate. When dealing with maintenance manpower supply problems, all this has to be taken into account. The airline maintenance certification system increases the complexity of the maintenance manpower supply planning problem, especially for a fleet with multiple aircraft types.

Our procedure for formulating a short-term layover maintenance plan has been based on a leading Taiwan airline (Airline C). The three stages of the procedure are outlined in Fig. 1. They

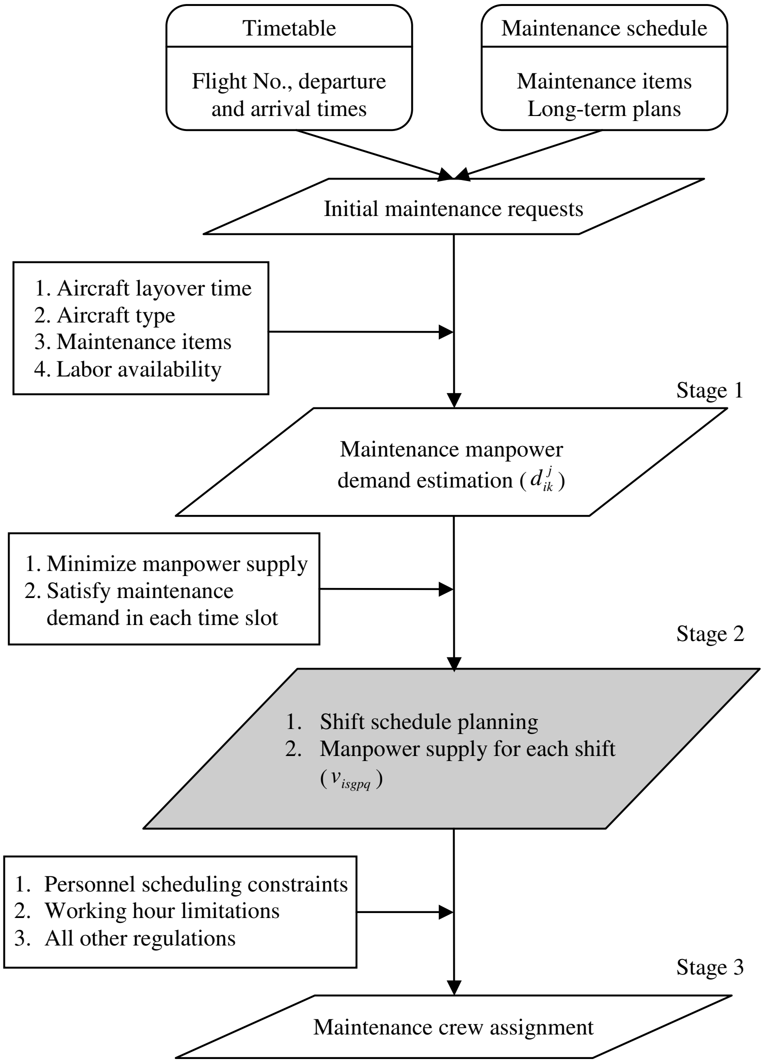

Fig. 1. Procedure for determining a short-term layover maintenance plan.

consist of: (1) the initial maintenance demand estimation, (2) the maintenance manpower supply plan, and (3) crew assignment.

The first stage is to aggregate all maintenance requests and then generate an initial schedule based on the flight timetable and the possible maintenance demands. The available holding time on the ground, the aircraft type, and the required maintenance tasks (usually converted to different types of working-hours) are all considered when estimating the manpower demand (man-hours) for each airplane in each maintenance time slot. The second stage is to set up a maintenance manpower supply plan to meet the required demand, as determined in the previous stage. A plan is generated, mentioning the number of shifts and the shift starting times, which facilitates the assignment of individual maintenance crew into appropriate shifts. Due to the inherent complexity of the scheduling problem, it is both difficult and time-consuming to efficiently set up a maintenance manpower supply plan that meets the required demand. The final stage is to assign individual crew members, while still satisfying the certification requirements, vacation schedules, and any associated regulations.

Note that the second stage and the third stage are usually separately in practice, because both manpower planning and crew assignment problems are huge and complicated. As is done in practice, in this research we set the objective in the second stage to be the minimization of the manpower supply. Although, in theory, this cannot guarantee that one obtains the most efficient crew assignment results, it usually serves as a good basis for obtaining a potentially low crew cost. This concept has been conventionally applied to the two-stage crew scheduling problems, including the crew pairing construction stage and the crew rostering stage. For examples, see Teodorovic (1988), Lavoie et al. (1988), Barnhart and Shenoi (1998), Yan and Chang (2002), and Yan et al. (2002).

For Airline C, the minimum maintenance team is called a squad, and currently includes four people, one of whom acts as the chief. The short-term layover maintenance tasks are classified and then listed on different working sheets. When a maintenance task is finished, the squad which has performed the task has to check off the listed items and leave a signature. The chief of the squad is responsible for this certification signature, to ensure the quality of maintenance tasks; therefore, a chief has to hold the appropriate certificates for the assigned maintenance tasks. The other three members of the squad do not necessarily have the corresponding certificates, because they work under the supervision of their chief. Hence, when we say the certificates are held by a squad, we actually mean that it is the chief who holds the certificates. Currently there are three shifts per day, and each shift has several maintenance squads on duty. A maintenance group is a minimum functional maintenance unit, composed of several squads. A maintenance group performs the same maintenance tasks in the same time slot; therefore, the squads in the same group should hold the same set of certificates. As a result, a maintenance group can also be looked as a certificate combination or a certificate set.

A maintenance crew needs to go through a series of training sessions in order to obtain a certificate. For Airline C, sending ground crew for training is an investment in employee skills but this also incurs extra costs, because employees cannot work during their training periods and the airline has to pay the training fees. Therefore, Airline C will only help its maintenance personnel to acquire at most three different types of aircraft maintenance certificates. In current practice, Airline C does not pay for its ground crew to obtain a fourth certificate. Technicians would need to pay their own way if they want to obtain a fourth certificate. Due to this policy, most of its maintenance personnel have at most only three different types of certificates.

Airline C wants to improve its efficiency in terms of human resource management for short-term maintenance. Therefore, a good maintenance manpower supply plan should help Airline C to better guide their training plans, recruitment policies, certificate combinations, and grouping or pairing principles. Because of the complicated certification system and the enormous number of constraints involved in short-term maintenance manpower supply planning, the traditional planning procedure, which depends on staff experience and intuition, is no longer practicable. Airline C, therefore, seeks systematic tools and methods to sketch out a future maintenance manpower supply plan. It also likes to explore different possibilities for improving the efficiency of its manpower supply plan.

This research focuses on planning for short-term layover maintenance manpower, which corresponds to the second step of the overall maintenance plan mentioned above. It should be mentioned that there are many ways by which a manpower supply plan's efficiency can be improved. One of these is the flexible management strategy. Flexible management strategies have become increasingly popular. They can increase the different degrees of freedom in the maintenance schedule and therefore conserve manpower. It has also been useful to apply the mathematical programming techniques commonly used in personnel scheduling. In this research, we employ some mathematical programming techniques and flexible management strategies to efficiently construct a manpower supply plan. To help the reader to understand the background, we first discuss some of the past research on personnel scheduling and flexible management strategies as follows.

Personnel scheduling problems can be classified into three groups, according to the industry characteristics: airline crew scheduling, mass transit crew scheduling, and generic crew scheduling problems (Beasley and Cao, 1996). Each group has often been discussed. Some examples are introduced below.

For airline crew scheduling: Lavoie et al. (1988) formulated the crew scheduling problem as a set covering problem where the column generation approach was used to solve it. Ryan (1992) formulated the airline crew rostering problem as a generalized set partitioning model. Langerman and Ehlers (1997) used a genetic algorithm plus a first-in-first-out (FIFO) method to solve crew scheduling problems. Nobert and Roy (1998) addressed the personnel scheduling problem at air cargo terminals. Their model formulated a manpower supply schedule for part-time and full-time employees given the demand. It allowed the flexible use of part-time employees, for different time periods, in order to meet the demand. Teodorovic and Lučić (1998) developed an aircrew rostering model that assigned approximately equal workloads to all crew members. Lučić and Teodorovic (1999) formulated an aircrew rostering problem as a multi-objective optimization problem and proposed a two-step solution procedure to solve the problem. The first step used the 'pilot-by-pilot' heuristic algorithm. The second step used the simulated annealing technique to improve the solution obtained from the first step. Yan and Chang (2002) developed a set-partitioning model and a column generation approach for airline cockpit crew scheduling problems. Yan et al. (2002) developed several integer programming models and column-generation-based algorithms to minimize airline crew costs and to plan the most appropriate individual pairings.

For mass transit crew scheduling: Caprara et al. (1997) developed crew scheduling models and algorithms that could solve both crew scheduling and crew rostering problems for a railway company. Higgins (1998) formulated a railway track maintenance crew problem as a mathematical program, and used Tabu search algorithms to solve the problem.

For generic crew scheduling: Beaumont (1997) formulated a manpower scheduling problem as a mixed integer program with the objective of minimizing the manpower supply. A mathematical programming package, CPLEX, was used to solve the problem. Brusco and Jacobs (1998) developed an algorithm to solve continuous tour scheduling problems by eliminating redundant columns, characterized by zero labor requirements in some planning periods. Brusco (1998) evaluated the performance of a dual all-integer cutting plane for the solution of generalized set-covering formulations of personnel tour scheduling problems. Alfares (1998) presented a two-phase algorithm to solve the cyclic manpower days-off scheduling problem.

Flexible management strategies have become more and more commonly used in modern business and industry. Of all the various flexible management strategies, the four that have recently attracted the most attention and discussion are: (1) numerical flexibility, (2) temporal flexibility, (3) wage flexibility, and (4) functional flexibility (Blyton and Morris, 1992). They are discussed in the following.

Numerical flexibility refers to the ability of employers to adjust the numbers of individuals working, and/or the number of hours worked by the employees, in response to changing organizational needs. This may include the use of short-term or temporary contracts. Numerical flexibility is usually provided by the employment of trainee, part-time, temporary, or subcontract types of workers. In the application of numerical flexibility to the airline maintenance problems, one possible strategy is to use both half-time and full-time employee at the same time; another possible strategy is to use a different number of technicians in a squad in different time slots, in response to changing maintenance demand. Both strategies are adopted in our model.

Temporal flexibility is related to variations in the number of hours worked. Flexible types of work arrangements include less than full-time work, job-sharing, career breaks and term-time work. Temporal flexibility in airline maintenance problems can be realized by the use of different shift starting times for different groups, which enables different number of technicians to be on duty in response to changing maintenance demands. Our model allows different shift starting times and different number of shifts.

Wage flexibility, also called financial flexibility, is related to the capacity of the remuneration system to respond to differing performance levels and changing labor demand/supply situations. Within the human resource management context, this type of flexibility includes performance-related-pay and, in some sectors, special arrangements that will facilitate the recruitment and retention of specialized staff. The salary structure is confidential in the airline industry; therefore, this study does not directly discuss a flexible wage strategy. Instead, we perform a salary sensitivity analysis for half-time and full-time employees, to demonstrate the influence of the different salary structures on the manpower supply.

Functional flexibility is related to an employer's ability to deploy and/or redeploy labor for different tasks, or to expand/contract the range of activities in which personnel are involved, according to changing organizational needs. In such a situation, staff may be required to use a wider range of skills and to demonstrate a wider range of competencies, so they can move from task to task. Such functional flexibility can be enhanced and/or facilitated through multi-skill training, team-based efforts, and so forth. Functional flexibility is not a preferable strategy for solving multiple aircraft maintenance problems, because the strict certification system limits any expansion of employee capabilities.

Most past studies of airline crew scheduling have focused on pilot and/or attendant scheduling problems. Airline maintenance manpower planning problems have very different characteristics from pilot and/or attendant scheduling problems, because airline maintenance ground crew always work at their base airport and do not move about. Furthermore, the maintenance crew schedule has to consider certification requirements, which is totally different from other scheduling problems. Because of this difference, it is difficult to directly apply general personnel scheduling models to maintenance manpower planning without some modifications. As well, we did not find any maintenance manpower supply planning models that incorporated flexible management strategies, although such management strategies have been widely recognized in the industry. In particular, in our review of the related literature we did not find any that addressed the particular issues of airline maintenance manpower supply, with multiple maintenance certification and flexible management strategies.

Therefore, we incorporate multiple maintenance certification, flexible management strategies and the related operating constraints, into the development of a mathematical programming model. By suitable modification of the model, we construct eight strategic models, associated with different combinations of flexible management strategies, which can help an airline more effectively manage its maintenance manpower supply. The models are formulated as mixed integer programs. The problem sizes are expected to be huge in real applications. To efficiently solve the problems we develop a solution algorithm. The rest of the paper is organized as follows: We first formulate the models as mixed integer programs. We then develop a solution algorithm to solve the problems. Thereafter, we perform a case study. Finally we give some conclusions.

2. Model formulation

In the section, we first formulate a maintenance manpower supply planning model (MM) containing three flexible management strategies. We then modify Model MM to construct eight different flexible strategic models. Finally, we discuss the problem sizes that occur in real application.

2.1. The maintenance manpower supply planning model (MM)

We focus on modeling a complicated short-term layover maintenance manpower supply plan, which is the second stage of an overall airline maintenance plan (i.e. the shaded area in Fig. 1). The maintenance demand for different types of aircraft in each time slot is used as input to our model. According to Airline C's maintenance demand profile, with a rotating timetable cycle, demand will fluctuate from time to time. Sometimes in off-peak hours, there is even no demand. Therefore, flexible strategies are a good idea, allowing Airline C to improve the efficiency of their maintenance manpower planning. If we take into consideration Airline C practices, three flexible strategies, based on numerical and temporal concept, can be proposed: flexible shifts, flexible squad members, and flexible working hours. The flexible shift strategy allows an employer to choose the preferable number of shifts 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) currently adopted by Airline C. In the flexible squad member strategy the number of squad members can be adjusted in response to changes, in demand in different time slots. Airline C currently has four people in a squad. The flexible working hour strategy allows the airline to hire both full-time and half-time employees. Currently Airline C has only full-time employees. Two types of flexibility are introduced in our model: full-time (8 h) shifts and half-time (4 h) shifts.

In order to reasonably reflect reality and to facilitate problem solving, the following assumptions, based on Airline C's current operations, are made:

1. The demand for each aircraft type in each time slot is known.
2. The model applies to planning for regular maintenance. Unexpected events or demands are not considered.
3. Since this study is aimed at building an efficient maintenance manpower supply plan and focuses on planning, we do not need to set an upper limit to the available maintenance manpower supply. The model has to be further modified if the current availability of manpower is considered, making manpower availability an additional set of constraints, which would limit the manpower supply during different time slots.
4. The objective function of our model is to minimize the total required manpower supply, while satisfying the maintenance demands in each time slot. Note that in some cases, the salary may be used to help in planning. That is, if the salary is correlated with the certificate combination, then the objective function could be modified to minimize the total salary expenses. However, for Airline C since the salary is not directly dependent on the certificate combination, it is difficult to set this as an objective function.
5. Since Airline C's flight timetable is rotated weekly, we use one week (seven days) as the planning cycle.
6. For the same type of aircraft, the shift starting time has to be the same every day of the week. In other words, if shift s is assigned to time J, then shift s occurs in the same time slot every day during the planning week, and has the same starting time. This assumption is in accordance with real practices. If the shift starting time for a maintenance team were to be changed every day, it would be very difficult for the employees to follow this type of schedule.
7. For the flexible working hour strategy, there are only two different shift lengths, 8 h for full-time employees and 4 h for half-time employees. This implies that the full-time employees have to work continuously for 8 h and half-time employees for 4 h.
8. A squad is the basic maintenance unit. Several squads compose a maintenance group, which is the minimum functional maintenance unit. The same maintenance tasks are performed for the same aircraft types in the same time slot, therefore squads in the same maintenance group hold the same combination of maintenance certificates. In other words, a maintenance group corresponds to a combination of certificates or a set of certificates.
9. Currently, the size of the maintenance squad is fixed at four persons in Airline C. The flexible squad member strategy allows for the squad size to vary, from two persons to four persons. However, for the same squad, within the same planning cycle the number of members is fixed.

This assumption is made because of practical concerns. Squad members work together to perform maintenance tasks. If members were to change from day to day, coordination would be very difficult and effectiveness reduced.

10. It is Airline C's policy to help its maintenance crew acquire, at most, three different types of maintenance certificates. A fourth type of certificate is not preferable. Therefore, in this study we assume that the maintenance crew can have, at most, three different maintenance certificates.
11. This model does not consider the crew assignment problem, which is handled after the manpower supply problem is resolved in practice.

Our model is based on actual operating procedures for Airline C. The objective is to minimize the total maintenance man-hours while satisfying the demand for every time slot. The basic notations are defined as follows:

W the set of days in a week. Since our planning period is one week (seven days), $W \equiv \{0\text{: Sunday}, 1\text{: Monday}, 2\text{: Tuesday}, 3\text{: Wednesday}, 4\text{: Thursday}, 5\text{: Friday}, 6\text{: Saturday}\}$.
i the ith day in a week; $i \in W$.
N the set of shift starting times in a day. The length of a time slot is set to be 1 h. Since there are 24 hours in a day; $N \equiv \{0, 1, 2, 3, 4, 5, \ldots, 23\}$.
j the jth time slot in a day; $j \in N$.
s the starting time of a shift s; $s \in N$.
C the set of all maintenance groups.
g the gth maintenance group; $g \in C$. As stated earlier, for overall maintenance needs, a combination of different squads and members in the same maintenance group holding the same maintenance certificates are needed in order to perform the same maintenance tasks.
T the set of all aircraft types used by the airline.
k type k aircraft; $k \in T$.
P the set of different squad sizes (i.e. different numbers of crew members).
p type p maintenance squad; $p \in P$.
m_p the number of persons in a type p maintenance squad.
Q the set of different types of work, to differentiate between full-time and part-time employees.
q type q work; $q \in Q$.
r_q the working hours for type q work.

The decision variables, x_s and v_{isgpq}, are defined as follows:

x_s the existence of a shift s (four or eight continuous working hours) in a particular 1-h time slot

$$\text{if } x_s = \begin{cases} 1, & \text{then time } s \text{ is a shift starting time, i.e. shift } s \text{ exists,} \\ 0, & \text{then time } s \text{ is not a shift starting time, i.e. shift } s \text{ does not exist.} \end{cases}$$

v_{isgpq} the number of type p squads for type q work in group g starting at shift s on day i.

The other variables and notations are defined as follows:

d_{ik}^{j} the maintenance manpower demand for the type k aircraft in time slot j on day i. It is measured by the number of persons.

y_{isgk}^{j} the least amount of manpower (man-hours) provided in group g starting at shift s on day i to maintain type k aircraft in time slot j. As mentioned earlier, a squad is the basic maintenance unit, so the scheduling and assignment are done at the squad level for every shift. However, the maintenance demand d_{ik}^{j} is estimated as the number of people required for every 1-h time slot. A squad v_{isgpq} may contain two to four persons and a shift for a squad runs a continuous 4 or 8 h period. To know whether the technicians on duty will satisfy the demand d_{ik}^{j} for a particular 1-h time slot, one has to aggregate all the on duty technicians in the particular hour, for all different squads, different groups, different types of work, and different shift starting times (i.e. v_{isgpq}). Therefore, v_{isgpq} cannot directly reflect d_{ik}^{j}, because d_{ik}^{j} and v_{isgpq} are measured differently. Hence, y_{isgk}^{j} is designed to bridge the difference in measurement between the number of squads for every shift (four or eight continuous hours) and the number of persons demanded for every 1-h time slot. Also, as illustrated in Fig. 1, d_{ik}^{j} is the estimated maintenance demand in man-hours obtained from stage 1, which serves as input to stage 2. Stage 2 is aimed at finding out the minimum number of squads, v_{isgpq}, for each shift. After all, y_{isgk}^{j} works as an auxiliary variable in stage 2 to bridge the input, d_{ik}^{j}, and the output, v_{isgpq}.

Z the objective value representing the total manpower supply.

l the lower bound of the total number of shifts in one day.

u the upper bound of the total number of shifts in one day.

B a very large value for ease of modeling.

H_{ij} the set of all shifts working in time slot j on day i. H_{ij} can be defined by Eq. (1) as follows:

$$\text{Full-time}: \begin{cases} \text{if } j \in \{0,1,\ldots,6\}, H_{ij} = \{(i',s') \mid i' = (i+6) \bmod 7, 17+j \leqslant s' \leqslant 23\} \\ \quad \cup\{(i',j') \mid i' = i, 0 \leqslant s' \leqslant j\}, \\ \text{otherwise}, \ H_{ij} = \{(i,s') \mid j-7 \leqslant s' \leqslant j\}, \end{cases} \quad \forall i \tag{1a}$$

$$\text{Half-time}: \begin{cases} \text{if} j \in \{0,1,\ldots,6\}, H_{ij} = \{(i',s') \mid i' = (i+6) \bmod 7, 21+j \leqslant s' \leqslant 23\} \\ \quad \cup\{(i',j') \mid i' = i, 0 \leqslant s' \leqslant j\}, \\ \text{otherwise}, \ H_{ij} = \{(i,s') \mid j-3 \leqslant s' \leqslant j\}, \end{cases} \quad \forall i. \tag{1b}$$

Fig. 2 shows two examples of full-time H_{ij} and part-time H_{ij} elements. For example, suppose $(6,8)$ represents a shift that starts on day 6, 00:00 and ends on day 6, 08:00. The full-time H_{69}, half-time H_{69}, and half-time H_{05} represent cases where the shifts do not cross-over two different days. Full-time H_{69} contains shifts $(6,2)$, $(6,3)$, $(6,4)$, $(6,5)$, $(6,6)$, $(6,7)$, $(6,8)$, and $(6,9)$. Half-time H_{69} contains shifts $(6,6)$, $(6,7)$, $(6,8)$, and $(6,9)$. Similarly, half-time H_{05} contains shifts $(0,2)$, $(0,3)$, $(0,4)$, and $(0,5)$. On other hand, the full-time H_{05} in Fig. 2 involves shifts that cross-over two different days. It contains shifts $(6,22)$, $(6,23)$, $(0,0)$, $(0,1)$, $(0,2)$, $(0,3)$, $(0,4)$, and $(0,5)$.

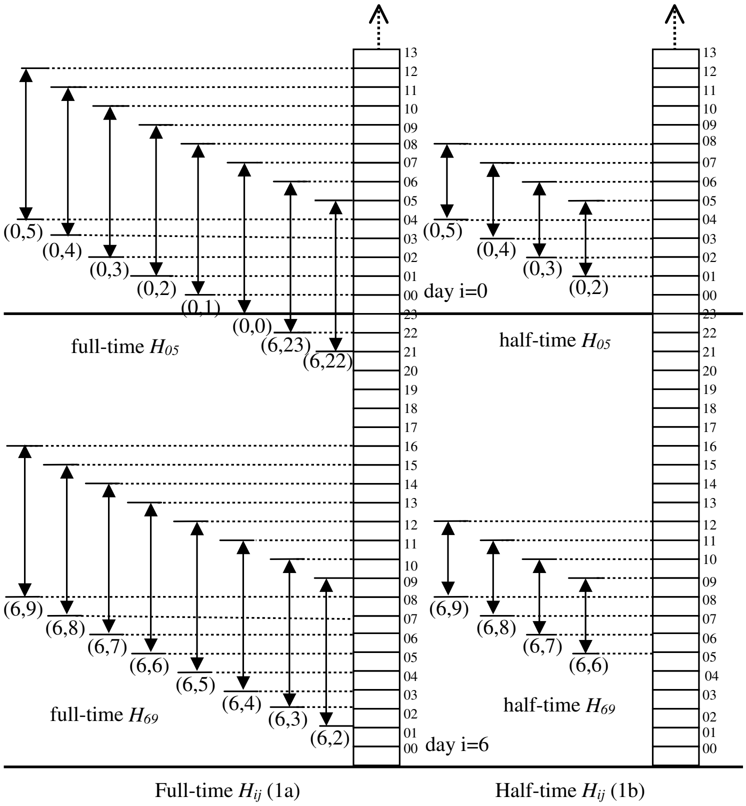

Fig. 2. Example for set H_{ij}.

Model (MM) is formulated as follows:

$$\min\ Z = \sum_{i\in W}\sum_{s\in N}\sum_{g\in C}\sum_{p\in P}\sum_{q\in Q} r_q m_p v_{isgpq} \tag{2}$$

$$\text{s.t.}\quad l \leqslant \sum_{s\in N} x_s \leqslant u, \tag{3}$$

$$\sum_{(i,s)\in H_{ij}}\sum_{g\in C} y^j_{isgk} \geqslant d^j_{ik}, \quad \forall i\in W,\ j\in N,\ k\in T, \tag{4}$$

$$\sum_{p\in P}\sum_{q\in Q} m_p v_{isgpq} \geqslant \sum_{k\in T} y^j_{isgk}, \quad \forall i\in W,\ s\in N,\ g\in C,\ j\in\{j \mid (i,s)\in H_{ij}\}, \tag{5}$$

$$\sum_{i\in W}\sum_{g\in C}\sum_{p\in P}\sum_{q\in Q} v_{isgpq} \leqslant Bx_s, \quad \forall s\in N, \tag{6}$$

$$x_s = 0 \text{ or } 1, \quad \forall s\in N, \tag{7}$$

$$v_{isgpq} \geqslant 0 \text{ and } v_{isgpq}\in I, \quad \forall i\in W,\ s\in N,\ g\in C,\ p\in P,\ q\in Q, \tag{8}$$

$$y^j_{isgk} \geqslant 0, \quad \forall i\in W,\ s\in N,\ g\in C,\ k\in T,\ j\in\{j \mid (i,s)\in H_{ij}\}. \tag{9}$$

Eq. (2) is the objective function which minimizes the total maintenance man-hours. Eq. (3) constrains the number of shifts within a reasonable range. Eq. (4) states that the assigned crew members must be able to meet the maintenance demands for all the different aircraft types in every time slot during their shift. Eq. (5) indicates that the total number of crew members, for every aircraft type, in every time slot, have to satisfy the least amount of supply that will meet the maintenance demands for every aircraft type, in every time slot. Note that it is difficult, using the defined v_{isgpq}, to relate the number of persons for each 1-h time slot with the number of squads for each shift. The auxiliary variable y^j_{isgk}, as well as Eqs. (4) and (5) are designed to facilitate the transformation. Eq. (6) means that a maintenance squad is assigned to a shift only when that shift exists. Eqs. (7) and (8) are integer constraints. Eq. (9) is a non-negativity constraint.

Note that, as previously discussed, the maintenance certification system increases the complexity of the maintenance manpower supply problem. For ease of modeling, Model (MM) does not explicitly formulate this requirement. According to assumption 8, certification is implicitly taken into account in the model as follows: Since members in the same group should hold the same set of certificates, in order to maintain the same type of aircraft, then when individuals are assigned to a maintenance group, the certificates they hold have to match the certificates for that group. Therefore, the requirement is automatically satisfied when the best maintenance group combination is sought. The efficiency of manpower supply in model (MM) comes from two parts. (1) Having a technician service more than one aircraft type during his/her shift; (2) having as few technicians as possible in on-duty maintenance groups to cover the necessary combination of certificates in every time period.

2.2. Flexible strategic models

Since Model (MM) contains three different flexible strategies: flexible shifts, flexible squad size, and flexible working hours, it can be modified (or decomposed) to construct different strategic models. The possible combinations are

$$C^3_0 + C^3_1 + C^3_2 + C^3_3 = 8,$$

where C^m_n means choosing n elements out of m elements.

In other words, eight flexible strategic models can be constructed from model (MM), specifically, M0, M0+a, M0+b, M0+c, M0+ab, M0+ac, M0+bc, and M0+abc, where the symbols "a", "b", and "c" denote the "flexible shift strategy", "flexible squad size strategy", and "flexible working hour strategy," respectively. Model (M0) does not incorporate any flexible strategy (so is called the basic model). Model (M0+a) incorporates the flexible shift strategy only. Model (M0+abc) considers all three flexible strategies, that is, model (M0+abc) is the same as model (MM). Since different strategy combinations can cause a different manpower supply, this helps the airline to find the best solution to meet its particular needs. For example, if half-time employees are not considered, then models with a flexible working hour strategy do not need to be applied. In particular, Models M0, M0+a, M0+b and M0+ab can be useful for maintenance manpower supply decisions. Table 1 illustrates the eight different models with different combinations of flexible strategies.

The eight models can be formulated by suitably setting the related variables or parameters such as x_s, P, p, m_p, Q, q, and r_q. For example, the basic model (M0) does not contain any flexible strat-

Table 1
Different flexible strategy models

Model	Flexible strategy		
	(a) Shift	(b) Squad size	(c) Working hours
M0			
M0+a	√		
M0+b		√	
M0+c			√
M0+ab	√	√	
M0+bc		√	√
M0+ac	√		√
M0+abc	√	√	√

egy, which corresponds to Airline C's current practices, that is three shifts per day, only full-time employees, and four people per squad. We can use this as an example of the basic model (M0): The three fixed shifts start at conventional starting times, 00:00, 08:00, and 16:00. Since we define a time slot as 1 h, we should set $x_0 = x_8 = x_{16} = 1$, otherwise $x_s = 0$. Set P contains only one element, a four person squad, so $p = 1$ and $m_p = 4$. Set Q also contains only one element, full-time employees; therefore, $q = 1$ and $r_q = 8$ (full-time, 8 h). The objective function (2) and constraints (3)–(9) can be formulated by plugging in the above values.

Similarly, for flexible strategic models containing a flexible shift strategy (i.e. M0+a, M0+ab, M0+ac, and M0+abc), if we allow the shifts to vary from 08:00 to 11:00, then the corresponding shift variables, x_8, x_9, x_{10}, and x_{11}, should be set to either 0 or 1, and all the other x_ss should be set to 0, since they are not allowed to be flexible. For flexible squad size strategy models (i.e. M0+b, M0+ab, M0+bc, M0+abc), if the squad size is allowed to vary from two persons to four persons, set P will contain three elements: a two person squad, a three person squad, and a four person squad; therefore, $p = 1$, 2, or 3, and the corresponding m_p variables are: $m_1 = 2$, $m_2 = 3$, and $m_3 = 4$. For models with flexible working hour strategies (i.e. M0+c, M0+ac, M0+bc, M0+abc), if we only consider two types of working hours: full-time/8 h and half-time/4 h, then set Q will contain two elements, full-time and half-time. $q = 1$ or 2, and the corresponding r_q variables will be: $r_1 = 8$ and $r_2 = 4$. By modifying the respective variables or parameters, eight different flexible strategic models can be developed.

2.3. Problem size

Model M0+abc (i.e. MM) considers all possible shifts, maintenance group combinations, and aircraft types. The problem size has become huge. Here, we use Airline C to demonstrate the complexity of this problem. If we consider a seven-day/one-week timetable, with 24 possible shift starting times per day, six different aircraft types, and 63 different maintenance groups ($C_1^6 + C_2^6 + \cdots + C_6^6 = 63$), three different squad sizes, two different types of working hours (full-time/8 h and half-time/4 h), there will be 24 different x_ss, 63,504 ($7 \times 24 \times 63 \times 3 \times 2$) v_{isgpq}s, and 508,032 ($7 \times 24 \times 63 \times 8 \times 6$) y_{isgk}^js. In total, there are 571,536 variables. As to the number of constraints, there are two constraints corresponding to Eq. (3), 1008 ($7 \times 24 \times 6$) constraints corresponding to Eq. (4), 84,672 ($7 \times 24 \times 63 \times 8$) constraints corresponding to Eq. (5), and 24 constraints corresponding to Eq. (6). There are already 85,706 constraints, without including variable constraints (7)–(9). It is both difficult and time-consuming to optimally solve a mixed integer program of such size. Note that the problem sizes of the other strategic models will be similarly huge in practice. Therefore, an algorithm is developed in the following section to efficiently solve the problem.

3. Solution algorithm

In this section, we develop an algorithm that will efficiently solve the maintenance manpower supply model (MM). This algorithm, with simplifications, can also solve other strategic models that are simpler than MM. The idea is that, based on implicit enumeration, some inferior feasible solutions can be cut-off, which narrows down the search region. The original problem (MM) is mainly broken down into two sub-problems. Optimal or near-optimal solutions can be achieved by systematically and recursively adjusting the solutions obtained from the two sub-problems.

3.1. The sub-problems

In the sub-problems, we reduce some of the variables and relax certain constraints on the original problem, so that the problem size can be reduced. The procedure is to first solve some variables in the first sub-problem, then, we fix the values of those variables obtained in the first sub-problem, and solve for the rest of the variables in the second sub-problem.

In the first sub-problem we assume that all the aircraft are of the same type, thus not considering differences in maintenance for different aircraft types. This is equivalent to assuming that all crew have certificates for all types of aircraft. In other words, differences among aircraft types do not affect the manpower supply planning. Model (MM) needs to be modified by removing the variables T and k, which are related to the aircraft type, and parameters C and g, which are related to maintenance certification. The formulation of the first sub-problem is as follows:

Maintenance manpower supply for uniform aircraft types (MM1)

$$\min \quad Z = \sum_{i\in W} \sum_{s\in N} \sum_{p\in P} \sum_{q\in Q} r_q m_p v_{ispq} \tag{10}$$

$$\text{s.t.} \quad l \leqslant \sum_{s\in N} x_s \leqslant u, \tag{11}$$

$$\sum_{(i,s)\in H_{ij}} \sum_{p\in P} \sum_{q\in Q} m_p v_{ispq} \geqslant d_i^j, \quad \forall i \in W, \ j \in N, \tag{12}$$

$$\sum_{i\in W} \sum_{p\in P} \sum_{q\in Q} v_{ispq} \leqslant B x_s, \quad \forall s \in N, \tag{13}$$

$$x_s = 0 \text{ or } 1, \quad \forall s \in N, \tag{14}$$

$$v_{ispq} \geqslant 0 \text{ and } v_{ispq} \in I, \quad \forall i \in W, \ s \in N, \ p \in P, \ q \in Q. \tag{15}$$

Here, v_{ispq} denotes the number of p-person squads for type q work starting at shift s on day i. d_i^j indicates the maintenance manpower demand at time slot j on day i. The other symbols are the same as in model (MM). Model (MM1) reduces the variables and the constraints associated with the different aircraft types, which implies that every crew member can maintain any type of aircraft. Theoretically, the solution for (MM1) becomes a lower bound of the optimal solution for the original problem (MM). However, the solution obtained from (MM1), which implies that technicians can have as many certificates as possible, cannot guarantee the feasibility, because Airline C currently only allows its technicians to have, at most, three different types of certificates. Therefore, we need a mechanism to generate a good feasible solution. In this step, we aim to find an appropriate number of shifts and their corresponding starting times, the values for which will be fixed and used as input data for the second sub-problem.

The second sub-problem is designed to solve for the optimal manpower supply for all possible certificate combinations, given the shifts and their starting times. The problem is formulated as follows:

Maintenance manpower supply for multiple aircraft types (MM2)

$$\min \ Z = \sum_{i\in W}\sum_{s\in F}\sum_{g\in C}\sum_{p\in P}\sum_{q\in Q} r_q m_p v_{isgpq} \tag{16}$$

$$\text{s.t.} \quad \sum_{(i,s)\in A_{ij}}\sum_{g\in C} y^{j}_{isgk} \geqslant d^{j}_{ik}, \quad \forall i\in W,\ j\in N,\ k\in T, \tag{17}$$

$$\sum_{p\in P}\sum_{q\in Q} m_p v_{isgpq} \geqslant \sum_{k\in T} y^{j}_{isgk}, \quad \forall i\in W,\ s\in F,\ g\in C,\ j\in\{j\mid (i,s)\in A_{ij}\}, \tag{18}$$

$$v_{isgpq} \geqslant 0 \text{ and } v_{isgpq}\in I, \quad \forall i\in W,\ s\in F,\ g\in C,\ p\in P,\ q\in Q, \tag{19}$$

$$y^{j}_{isgk} \geqslant 0, \quad \forall i\in W,\ s\in F,\ g\in C,\ k\in T,\ j\in\{j\mid (i,s)\in A_{ij}\}. \tag{20}$$

Although fixing the number of shifts and their starting times can reduce the problem size of model (MM2) to smaller than the original model (MM), the certification considerations for multiple aircraft types are still large, which means a large number of variables in the second sub-problem. For example, Airline C allows each crew member to have at most three different certificates. Since Airline C has six different types of aircraft, the number of possible certificate combinations for a group is $C^6_3 + C^6_2 + C^6_1 = 41$. Thus, the variables with subscript g will have 41 different combinations, not to mention the other subscript indices. If the possible combinations are not many, then a complete enumeration might be feasible, but when the possible combinations become large, particularly in other applications, a complete enumeration may not be a good approach to the seeking of a better solution and, therefore, another mechanism is needed.

In this study a mechanism is developed that can implicitly enumerate all possible certificate combinations. The underlying idea is that the more certificates that maintenance crews have, the better the solution system that can be reached. This is because more types of aircraft can be maintained in the same time slot, which reduces the idle time. If a person only holds one type of certificate, he/she may be idle much of the time, since he/she can only maintain one type of aircraft, and cannot be assigned any maintenance tasks for other types of aircraft. Therefore, we abandon combinations with fewer types of certificates, and keep the combinations with more type, which will certainly correspond to a better solution. In addition to obtaining the initial shifts and their corresponding starting times from model (MM1), the remaining combinations are explicitly enumerated, then used as input to model (MM2). In this way, the number of variables can be significantly reduced and model (MM2) can be solved more efficiently.

The above example illustrates this idea. There are a total of 41 possible certificate combinations for a group. The combinations of holding three different certificates ($C_3^6 = 20$) are better than those of holding one or two certificates ($C_2^6 + C_1^6 = 21$). Hence, we can cut out 21 of 41 possible combinations and need only search 20 different combinations, since the best solution should be one of these. This mechanism removes some feasible solutions, while guaranteeing that the remaining ones are the best, thus reducing the search area. Note that if the number of combinations is very large, it might still be time-consuming to find the best one. For this, one may consider incorporating such advanced neighborhood search techniques as tabu search, simulated annealing or threshold accepting (e.g. see Yan and Luo, 1999), to improve the search efficiency. This could be a direction for future research.

It should be mentioned that the solution obtained from model (MM2) has the best certificate combinations for a given number of shifts and their starting times solved from model (MM1). This does not, however, guarantee the optimal solution. If the current solution obtained from model (MM2) is not satisfactory under a preset computation limit, then another iteration can be launched. The new iteration starts from search for a shift schedule (shifts and their corresponding starting times) based on the current number of shifts and their starting times. This search can proceed in two directions. First, the current number of shifts can be fixed and a new set of shift starting times generated. Model (MM2) is then solved again based on the new times. If the solution is still not satisfactory, we then move to the second option wherein both the number of shifts and their corresponding starting times are changed. We use the new number of shifts and starting times as input to model (MM2), and solve to obtain a new solution. The above procedure is performed repeatedly until the optimal solution (i.e. its objective is the same as the lower bound from MM1, or all possible number of shifts and their starting times have been tried) or a satisfactory solution (e.g. its objective is within a tolerable error gap of the lower bound from MM1) is reached; or a preset number of shift schedules have been tried. Of course, advanced neighborhood search techniques, for example, tabu search, simulated annealing or threshold accepting (e.g. see Yan and Luo, 1999), could also be applied in the shift schedule search procedure. Other mechanisms can also be researched in future.

As discussed earlier, the problem size has been significantly reduced because the problem is broken into two sub-problems. The search combinations are, therefore, substantially reduced. We can use the same example discussed earlier to illustrate the reduced problem size corresponding to a combination. Consider a seven-day/one-week timetable, with 24 possible shifts in one day, six different aircraft types, and at most three different certificates for each maintenance crew member, three different squad sizes, two different types of working hours, and eight different flexible strategies ($C_0^3 + C_1^3 + C_2^3 + C_3^3 = 8$). For problem (MM1), there are 24 integer variables x_s and 1008 ($7 \times 24 \times 3 \times 2$) integer variables v_{ispq}, two constraints for Eq. (11), 168 constraints for Eq. (12), and 24 constraints for Eq. (13). Altogether, there are 1032 integer variables and 194 constraints in model (MM1) excluding the variable constraints. As for model (MM2), the x_ss are no longer decision variables, since they have been given by model (MM1). If we suppose the number of shifts obtained from model (MM1) is n, then MM2 tells us that a particular certificate combination, there are $7 \times n \times 3 \times 2$ integer variables v_{ispq}, $7 \times n \times 8 \times 6$ real variables y_{isgk}^j, $7 \times n \times 6$ constraints for Eq. (17), and $7 \times n \times 8$ constraints for Eq. (18). In total, there are $42 \times n$ integer variables, $336 \times n$ real variables, and $98 \times n$ constraints (excluding the variable constraints) for the combination generated by model (MM2). It is obvious that the problem sizes for models (MM1) and (MM2) have been reduced; hence, the computational effort should be less than that required to solve the original problem (MM). The mathematical programming solver, CPLEX, is used to optimally solve the reduced problems. This mechanism is now used to develop the following algorithm.

3.2. The solution algorithm procedure and its advantages

The solution algorithm procedure is shown in Fig. 3. The steps are listed in detail as follows:

Step 1: *Initial shift schedule.* Solve (MM1) to obtain a good initial shift schedule. The solution forms a lower bound to the original problem (MM).

Step 2: *Shift schedule generation*
1. If the initial shift schedule has not been run, then the current shift schedule is equal to the initial shift schedule.
2. If all possible shift schedules or the preset number of shift schedules have been tried, then stop.
3. If the initial shift schedule has been tested and all shift starting times have not been searched, then new shift starting times can be generated. The current shift schedule is equal to the initial number of shifts plus the newly generated starting times.
4. If the initial shift schedule has been tested and all shift starting times have been searched, then generate a number of new shifts and starting times. The current shift schedule is equal to the newly generated number of shifts plus their starting times.

Step 3: *Certificate combination reduction.* Discard any possible combinations with fewer certificates. Keep only combinations where more certificates are held.

Step 4: *Certificate combination generation*
1. If all certificate combinations have not been tried, then generate a combination for a maintenance group based on the remaining certificate combinations reduced in Step 3.
2. If all certificate combinations have been run, then go to Step 2.

Step 5: *Solution improvement.* The shift schedule obtained from Step 2 and the certificate combination generated from Step 4 are used as input data to solve problem (MM2) with the mathematical programming solver, CPLEX. The solution obtained in this step is a feasible upper bound.

Step 6: *Solution update.* Update the incumbent solution with the feasible upper bound obtained from Step 5. If the updated incumbent solution is satisfactory, then Stop; else go to Step 4.

The proposed algorithm has several advantages:

1. It breaks the original complicated problem down into two sub-problems, thus reducing the problem size and increasing the computational efficiency.

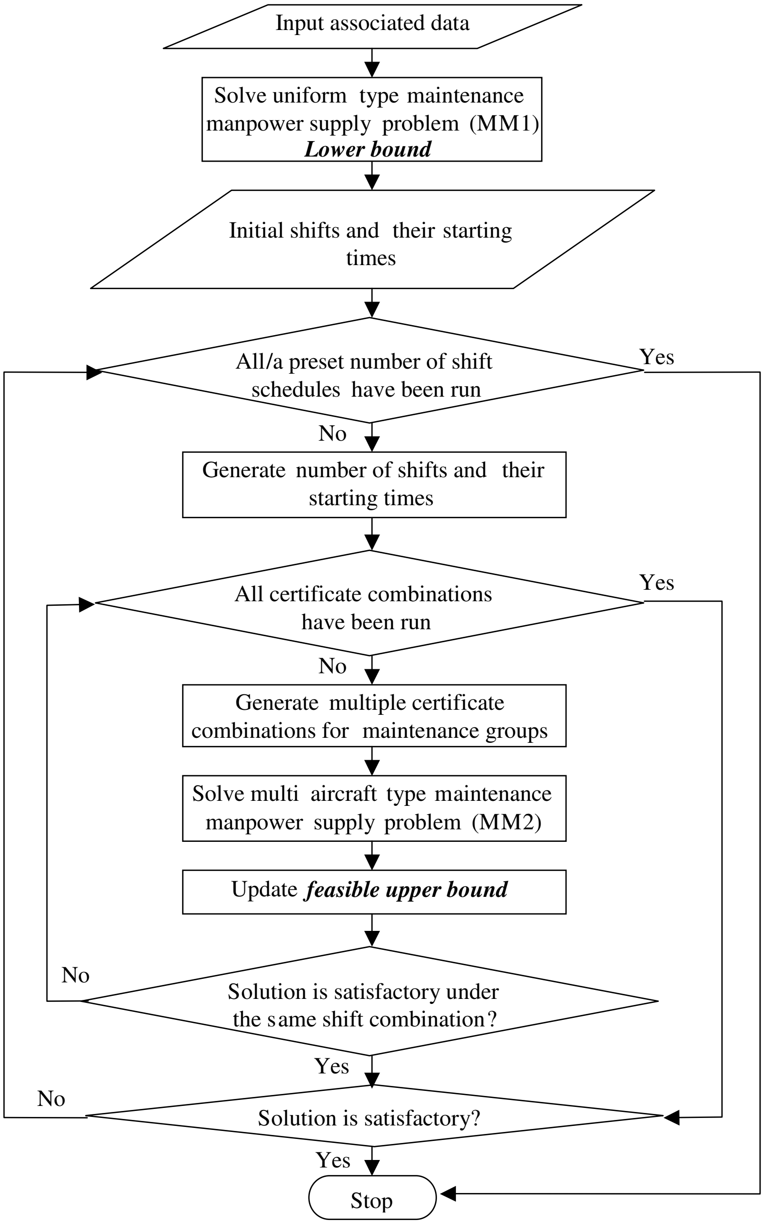

Fig. 3. Solution algorithm procedure.

2. Since the algorithm is based on implicit enumeration, it can be used to solve for the optimal solution if the solution satisfactoriness is set to be equal to the optimal solution, or to solve for a near-optimal solution if the solution satisfactoriness is set to be within a tolerable error gap of a lower bound, e.g. the solution from MM1. This provides the flexibility for a trade-off between computational efficiency and solution accuracy.

3. The shift schedule is first determined; this is then treated as input data for sub-problem (MM2), to eliminate the number of variables. A feasible upper bound for the manpower supply is then found by solving (MM2). The proposed algorithm can systematically solve the variables step by step, thereby reducing the number of variables and constraints, which dramatically improves the efficiency.
4. The sub-problem (MM1), which usually generates an appropriate shift schedule, could provide a good headstart on the solution procedure, thus reducing the search range.
5. In the sub-problem (MM2) we have to find the best certificate combinations for multiple types of aircrafts. The proposed mechanism for certificate combination search procedure can reduce the search for combinations from 41 to 20. Since solving a certificate combination is equal to solving a sub-problem (MM2), the mechanism could reduce the computational burden by about one-half. In addition, the developed mechanism first generates a certificate combination and then solves MM2 based on this combination. This means that different combinations can be solved separately in MM2, thus the original large problem size, for all certificate combinations, can be decomposed into smaller and independent problems, which can be optimally solved using CPLEX.
6. The upper bound and the lower bound are provided by the solution algorithm procedure. These could be useful indices for future practitioners.

4. Case study

We use Airline C's short-term layover schedule and maintenance demand from June 5, 2000 to June 11, 2000 as our test data. They have six different types of aircraft, 51 aircraft in total, requiring 481 maintenance items altogether (preflight checks: 146 items, transit checks: 152 items, and daily checks: 183 items). The mathematical programming software, CPLEX, coupled with the C programs developed during this research, is used to solve the problems. The test platform was a personal computer (Intel Pentium 4 1.8 GHz) with 1G MB SDRAM, in the environment of Microsoft Windows 2000.

Fig. 4 illustrates the average hourly maintenance demand in man-hours per day. The largest maintenance demand appears from 20:00 to 23:00. The other peak periods occur at 6:00 to 8:00, 11:00 to 13:00, and 15:00 to 16:00.

The improvements found by the proposed flexible strategic models are compared to Airline C's current schedule. Airline C has three fixed shifts, starting at 0:00, 08:00, and 16:00. Every shift is fixed at 8 h, because all the employees are full-time. The squad size is also fixed at four persons. This corresponds to model (M0) in Table 1. The test scenarios, compared with the current situation, are listed in Table 2.

In preliminary tests, although the proposed algorithm has shortened the computational burden, the solution algorithm still took a lot of computational effort, especially for model (MM1). In a trade-off between computational efficiency and solution accuracy, we cut off the solution algorithm after 600 s of CPU time, in the step for solving a certificate combination using CPLEX,

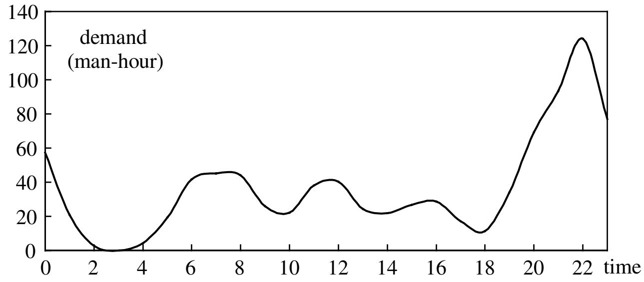

Fig. 4. Average hourly maintenance demand profile per day.

Table 2
Test scenarios

Flexible strategy	Current situation	Test scenarios
Number of shifts	3	3, 4, 5, 6
Shift starting times	00:00, 08:00, 16:00	Can start at any time in a day
Squad size (persons)	4	2, 3, 4
Working hours	8	8 and 4

since after this time the solutions rarely improved. For ease of testing, we set the solution satisfactoriness to be within a 5% error gap from the lower bound obtained from MM1, or until all certificate combinations from the initial shift schedule have been tested. The results show that most of the test problems could be solved to within a worst error gap of 5%, with only two problems being slightly more than 5%, in at most 625.9 s (CPU time), showing that the solution algorithm could be efficient for solving realistically large problems. Surely, if higher satisfactoriness or more shift schedules are set for the stopping criterion, then better results would be obtained.

We first analyze the strategy of a flexible number of shifts using Model MM, i.e. Model M0 + abc. We varied the number of shifts from 3 to 6, and their starting times could be any time slot in a day. As shown in Table 3, the results indicate that six shifts (starting at 05:00, 13:00, 19:00, 20:00, 21:00 and 22:00, respectively) would lead to the best solution. This is because a larger number of shifts implies a larger set of feasible solutions, which results in a better solution. We can observe from the results that the best shift starting times match the maintenance demand curve (Fig. 4). For example, the peak maintenance demand is from 5:00 to 8:00, from 11:00 to 13:00, and from 20:00 to 22:00. The best shift starting times are 5:00, 13:00, 19:00, 20:00, 21:00 and 22:00, which roughly match the demand trend. Fig. 5 illustrates the objective values for the cases where there are different numbers of shifts. The four-shift case solution is significantly improved over the three-shift case. When the number of shifts is greater than four, the improvement of the objective value is relatively small. After all, although increasing the number of shifts can improve the schedule efficiency, when the number of shifts is more than four per day, it does not help save much manpower.

Table 3
Results for the proposed flexible strategic models

Sub-problem	Shift upper bound	Integer solution (man-hours)	Real solution (man-hours)	Gap between real solution and integer solution (%)	Computation time (s)	Worst error gap (%)[a]
Model (MM1)	3	9956	9952	0.04	600.062	–
	4	8044	7684	4.48	600.094	–
	5	7724	7724	0	429.797	–
	6	7672	7144	6.88	600.141	–
Model (MM2)	3	10,364	10,364	0	11.906	4.10
	4	8424	8424	0	169.671	4.72
	5	8152	8152	0	200.187	5.54
	6	8052	8052	0	625.954	4.95

[a] Note: worst error gap = (MM2 − MM1)/MM1.

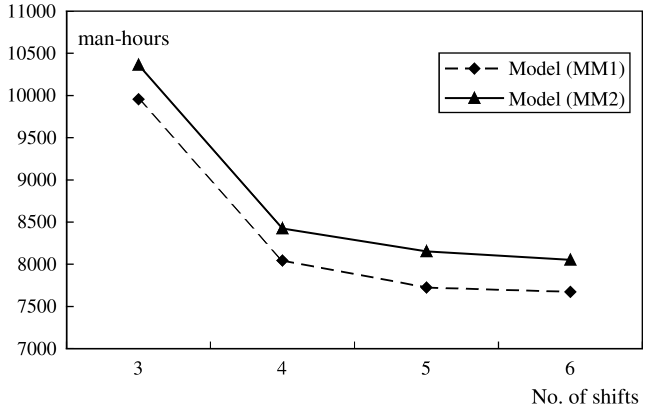

Fig. 5. Objective values for different shift upper bounds.

The flexible working hour strategy is examined next. Table 4 compares the models that incorporate the flexible working hour strategy with models that do not adopt this strategy. For ease of comparison, the number of shifts in all models is fixed at 3 (the same as the current number of shifts used by Airline C), while the corresponding shift starting times can be adjusted. The flexible working hour strategy allows for the use of both full-time and half-time employees. In order to compare the two models on the same basis, we convert half-time employees to an equivalent number of full-time employees (i.e. two 4-h half-times are equal to one 8-h full-time). The results show that flexible working hours can save manpower by at least 4.82% over models without a flexible working hour strategy. In addition, by adopting a flexible working hour strategy together with a flexible shift strategy, significantly more manpower can be saved (15.29% from M0+a to M0+ac and 15.82% from M0+ab to M0+abc), while utilizing only a flexible working hour strategy or a flexible working hour strategy together with a flexible squad size, leads to relatively less manpower saving (4.82% from M0 to M0+c and 5.01% from M0+b to M0+bc).

Table 4
Influence of flexible working hour strategy

	M0	M0+c	Improvement (%)
MM1	1624	1564	3.69
MM2	1700	1618	4.82
	M0+a	M0+ac	Improvement (%)
MM1	1524	1274	16.40
MM2	1596	1352	15.29
	M0+b	M0+bc	Improvement (%)
MM1	1590	1529	3.84
MM2	1656	1573	5.01
	M0+ab	M0+abc	Improvement (%)
MM1	1489	1244.5	16.42
MM2	1539	1295.5	15.82

Table 5
Influence of flexible squad size strategy

	M0	M0+b	Improvement (%)
MM1	1624	1590	2.09
MM2	1700	1656	2.59
	M0+a	M0+ab	Improvement (%)
MM1	1524	1489	2.30
MM2	1596	1539	3.57
	M0+c	M0+bc	Improvement (%)
MM1	1564	1529	2.24
MM2	1618	1573	2.78
	M0+ac	M0+abc	Improvement (%)
MM1	1274	1244.5	2.32
MM2	1352	1295.5	4.18

A similar analysis is applied to the flexible squad size strategy. Table 5 lists the results for flexible squad size models. The number of shifts for all models is fixed at three for ease of comparison, and full-time employee equivalence is also used as the manpower unit (e.g. one half-time employee equals 0.5 full-time employee equivalence). Models that adopt a flexible squad size strategy improve between 2.59% and 4.18% over those that do not adopt a flexible squad size. Note that in comparison with the flexible working hour strategy, the flexible squad size strategy is less effective.

In Tables 4 and 5 we also summarize the results for the eight different flexible strategic models. Table 6 summarizes the various flexible strategic models in full-time employee equivalence. Fig. 6 plots the trend for different flexible strategic models in full-time employee equivalence. The basic

Table 6
Summary of all flexible strategic models in full-time employee equivalence

Sub-problem	M0	M0 + a	M0 + b	M0 + c	M0 + ab	M0 + ac	M0 + bc	M0 + abc
Model (MM1)	1624	1524	1590	1564	1489	1274	1529	1244.5
Model (MM2)	1700	1596	1656	1618	1539	1352	1573	1295.5
Worst error gap (%)[a]	4.68	4.72	4.15	3.45	3.36	6.12	2.88	4.10

[a] Note: worst error gap = (MM2 – MM1)/MM1.

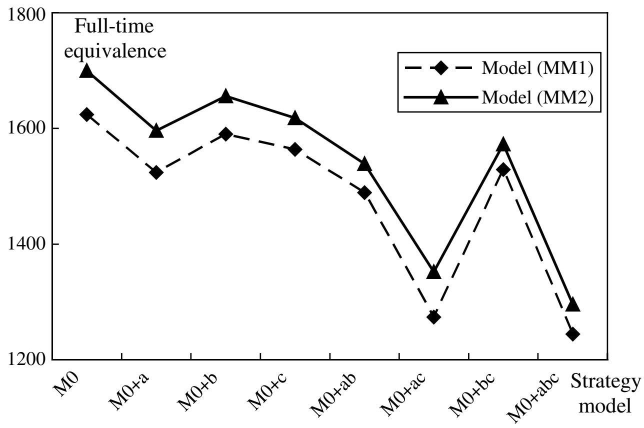

Fig. 6. Full-time employee equivalence for various flexible strategic models.

model M0 (without any flexible strategy) requires the largest number of people to finish the same maintenance tasks, while the model that includes all the flexible strategies (M0 + abc) requires the least number of people. Therefore, by adopting the more flexible strategies the airline could save more manpower. Note that, there might be some disadvantages to adopting flexible strategies, such as safety requirement assurance for part-time technicians, an increase in overhead expenses due to the expansion of part-time technicians, an increase in the difficulty of managing an expanded number of technicians, etc. However, these disadvantages are airline specific. Before deciding on a suitable manpower plan, the airline should evaluate the trade-off between the advantages and the disadvantages. Nevertheless, the model results still provide a good reference for the analysis of such a trade-off. In Table 6 and Fig. 6 we also find that, for the single flexible strategy, strategy M0 + a (flexible shifts) is the most effective strategy, while the second is strategy M0 + c (flexible working hours), and the last is strategy M0 + b (flexible squad size), i.e. M0 + a < M0 + c < M0 + b. This implies that a flexible shift strategy is more effective than a flexible working hour strategy, which is in turn more effective more than a flexible squad strategy. For the combined flexible strategies, strategy M0 + ac is better than strategy M0 + ab, which is better than strategy M0 + bc, that is, M0 + ac < M0 + ab < M0 + bc. The computation times for the strategic models are listed in Table 7. Since the majority of the computational effort in the proposed algorithm is spent in solving model (MM1), Table 7 only lists the computation times for model (MM1). Although the strategic model M0 + abc required the longest computation time, it is still

Table 7
Computation times for the various strategic models

Model	M0	M0+a	M0+b	M0+c	M0+ab	M0+bc	M0+ac	M0+abc
Model (MM1) integer variables	21	168	63	42	504	126	336	1008
Computation time (s)	0.329	1.061	1.251	0.854	378.186	3.098	8.287	614.515

efficient in the planning stage. The basic model, M0, required the least computation time. In general, including more strategies in the model results in more computation time. We also found that the number of integer variables may be the key to the computation time; that is, the more integer variables, the greater the computational effort. This could be due to the use of the branch and bound approach that is designed in CPLEX for solving the sub-problems.

In the previous tests it was all assumed that half- and full-time employees were all paid by the hour, equivalently. However, in reality, part-time employee salaries are usually different from full-time employees. Most part-time employees are paid more per hour than full-time employee, because the company usually offers a package of benefits to its full-time employees, for example, health insurance, on-the-job-training and so on. In order to examine the influence of the salary structure on the manpower supply, we perform a sensitivity analysis of the half- and full-time salary different combinations, using Model M0+abc. The hourly payment for full-time employee is fixed to be one unit and the hourly payment for half-time employee varies from 0.1 to 3 units. Fig. 7 converts man-hours (the original objective value) to payment units by multiplying half- and full-time employee working hours to hourly payment units. As the ratio of half-time/ full-time employee hourly payment increases, the total payment increases. However, after the half-time employee's hourly payment becomes double that of the full-time employee's hourly payment, the total salary does not increase much. This is because when the half-time employee's payment is more than double the full-time employees, having half-time employees on duty is too costly. One should reduce the use of half-time employees and use as many full-time employees as possible. In Fig. 8 the number of half- and full-time employees is separated with respect to the

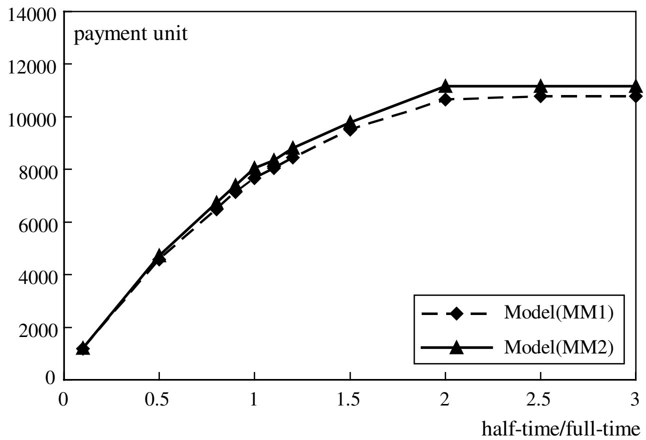

Fig. 7. Objective values under different half-time/full-time salary ratios.

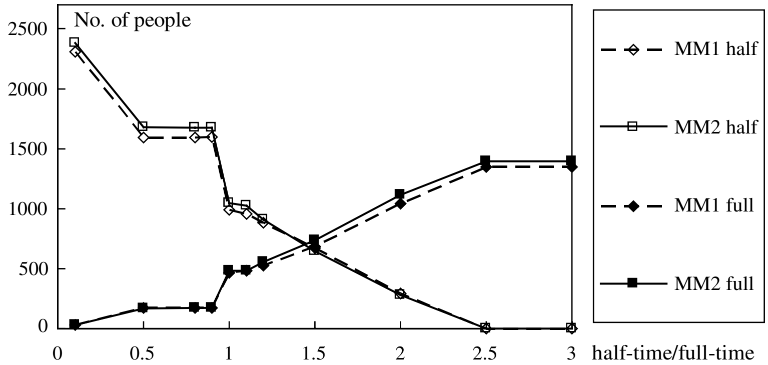

Fig. 8. Number of half-time/full-time employees under different half-time/full-time salary ratios.

different payment ratios. When the half-time hourly payment is low, a better strategy would be to use a higher portion of half-time employees. However, when the half-time payment is too costly, the optimal strategy would be to use a higher portion of full-time employees. Figs. 7 and 8 show that the salary structure could have a critical influence on manpower supply planning. The results indicate that airlines should take their salary structure into account in crew scheduling process.

Temporal demand is also an important factor. To preliminarily analyze the influence of different demand patterns on manpower supply, we design the following tests. For ease of testing using the above practical demand data, we fix the number of shifts per day to be three and the shift working hours to be eight, in order to have the same basis for comparison. In other words, the flexible strategies are not applied. We started with three shifts at 0:00, 8:00, and 16:00. These three shifts are moved 1 h later until they begin at 7:00, 15:00, and 23:00. This makes eight different shift scenarios to solve using Model M0. Note that with the given demand pattern, eight different shifts can be horizontally shifted, reflecting relatively eight different demand patterns, per shift. Fig. 9 illustrates the full-time employee equivalence (number of full-time technicians for one week) for different time-slot manpower supplies, under the given demand pattern. Note that the value associated with the time slot 0 denotes the full-time employee equivalence of the three shifts 0:00, 8:00, and 16:00. Also, note that the right most data set (7:00, 15:00, 23:00) is the same as the left most data set (23:00, 7:00, 15:00). When the three shifts start at 6:00,

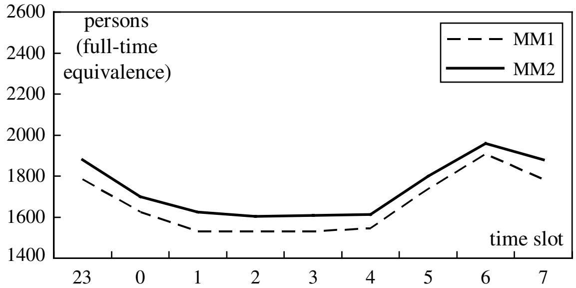

Fig. 9. Full-time employee equivalence for different time-slot manpower supplies under the same demand pattern.

14:00, and 22:00, or 23:00, 7:00, and 15:00, there is not a good manpower supply plan, because the manpower supply patterns do not follow the temporal demand variation. The worst case and the best case have difference in full-time employee equivalence of almost 1/3, which implies that the capability of manpower supply to respond to demand is important. Note that the number of technicians in all eight scenarios are more than the optimal value obtained from Model M0+a, with three shifts, by at least eight persons (full-time employees) for both MM1 and MM2. The results show that the models containing a flexible shift strategy should more effectively plan manpower supply in relation to different temporal demands, in practice. Similar analyses for other demand patterns and/or among different demand patterns, with other flexible management strategies, can be performed in the future.

5. Summary and conclusions

Most researches in airline crew scheduling problems have only addressed pilot or attendant scheduling problems. Past efforts have seldom focused on the airline maintenance manpower supply planning problem. The maintenance certification system is a unique feature for maintenance crew scheduling problem, which makes the pilot or attendant scheduling models difficult to apply. Of the different levels of maintenance plans, short-term layover maintenance, performed before and after a service flight, is essential for flight safety and timetable punctuality. Therefore, a good short-term layover maintenance manpower supply should help airlines to set up guidelines for training plans, recruitment policies, certificate combinations, and grouping or pairing principles, which could significantly reduce their operational costs. In order to further improve manpower supply efficiency, this study adopts the recently popular flexible management strategies that have been applied by many industrial organizations. In this research, we consider multiple maintenance certificates, three flexible strategies and the related operating constraints, to develop a set of models that can help an airline find an effective maintenance manpower supply plan. The models were formulated as mixed integer programs, with the objective of minimizing the total maintenance manpower supply in terms of man-hours, while satisfying all the requirements and the demands in each time slot.

There are many possible shift schedule combinations, maintenance group combinations, and certificate combinations, making the proposed mixed integer program for real problems both complicated and huge. Hence, we have developed an algorithm to efficiently solve the problems. Based on the technique of implicate enumeration the proposed algorithm has the capability to solve the problems optimally or near optimally, primarily by breaking the original problem down into two sub-problems. We first assume a uniform type of aircraft to find the best potential shift schedule. In the second step multiple types of aircraft are considered by generating better multiple certificate combinations for maintenance groups, and then, given the shift schedule and maintenance group certificate combinations, the problem is solved for manpower supply. Thus, we can reduce by about half of the certificate combinations during the solution procedure. The algorithm solves the two sub-problems sequentially to obtain an optimal solution or near optimal solution. By setting different levels of satisfactoriness, the proposed algorithm provides a flexibility to make trade-off between computational efficiency and solution accuracy.

The proposed model's effectiveness and the solution algorithm's efficiency are tested using the maintenance schedule of a leading Taiwan airline. From the preliminary test results, they are shown to be both efficient and effective, in terms of a manpower supply plan. In future, we plan to do research on the down-stream maintenance crew assignment problems, the third stage shown in Fig. 1, to complete the maintenance crew schedule plan.

Acknowledgments

This research was supported by a grant (NSC 90-2211-E-008-046) from the National Science Council of Taiwan. We would like to thank the airline for providing the test data and its valuable opinions on this research. We would also like to thank the anonymous referees for their helpful comments and suggestions on the presentation of the paper.

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