Research on A Machine-Learning Based Scheduling Algorithm for Air Traffic Controllers

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Abstract—Workload of air traffic controllers has increased over the years owing to the rapid development of civil aviation. To enhance the security control of air traffic, a more reasonable scheduling method needs to be put in place to ensure enough rest break for air traffic controllers. This paper has first reviewed previous worldwide studies on linkages between scheduling method and controller workload. It then discusses scheduling methods used in current air traffic facilities and their potential drawbacks. As a potential response to these drawbacks, a machine-learning based scheduling algorithm is proposed by the paper, along with a comparative verification to prove its feasibility and practicality.

1. Introduction

Recent rapid developments of civil aviation and low-altitude airspace management have led to significant growth in air flow and airspace complexity, which in turn brings more challenges to air traffic control. In 2018, Civil Aviation Administration of China provided air traffic control services to 5.624 million flights, a 5.65% growth compared with that of 2018. The daily flight number has reached to 15409, 2.2 times that of 2009. Ever since 2009, China’s flight operations have grown at an annual rate of 9%. However, available airspaces only grow with an annual rate of 3%, which is bringing increasing pressures to air traffic control system.

While there is a rising demand for air traffic controllers (hereinafter referred to as controllers), the system has also raised its job qualifications for controllers. However, the growth rate of available controllers is incomparable to that of air flow. This is due to the long training cycle and high turnover rate brought by the work pressure of controllers. The limited growth of available controllers, combined with the 24-hour shift schedule, require a reasonable scheduling system to ensure that controllers maintain high concentration during their shifts and safely command aircraft operations. The number of available controllers, along with their physical fatigue and mental state, are significant factors for the scheduling system.

Though Manual scheduling is commonly used, it is more feasible in places with fewer control positions. The scheduling complexity grows with the number of positions, thereby decreasing the working efficiency of schedulers. Meanwhile, manual scheduling makes it harder for authorities to conduct statistical analysis on scheduling data. Moreover, if the scheduling is irrational due to the subjectivity of manual scheduling, it will increase the fatigue of controllers and compromise their cognitive ability and alertness. Unsafe behaviors, such as wrong decision making, memory omissions
and illegal operations, may appear among controllers and endanger flight safety. Therefore, it is imperative to carry out scientific and intelligent scheduling for controllers, based on their abilities and positions.

2. Literature Review

2.1 Current Research on Scheduling Systems
Scheduling [1] is a process of generating a work schedule for a limited timespan that meets certain constraints according to the work plan. Fair and reasonable scheduling results may significantly increase the motivation and work efficiency of staff.

Experts in the civil aviation field showed great commitment to the scheduling system of controllers and human resource management of the controlling team. In-depth research has been done to optimize the scheduling system and analyzed the workload of controllers.

Literature Reviews show that certain controlling positions have larger influence on controller’s health conditions compared with other positions. In 2007, Costa adopted Standard Shiftwork Index (SSI) to evaluate the health conditions of controllers and concluded that radar controllers in regional center had worse health conditions compared with controllers in other facilities [1]. Meanwhile, experts have also analyzed the impacts of different scheduling system. For instance, Cruz and others have compared the effect of clockwise and counterclockwise rotating shift schedules on sleep disruption and complex task performance of controllers. They argued that clockwise rotating does not bring better outcome [2-3] (2002). One of the major researches focused on health condition was the effect of fatigue. Nealley and Gawron summarized the indicator system affecting controller fatigue and the impact of fatigue on controllers [4] (2015).

In China, Zhu Xiaomei and others have adopted Analytic hierarchy process to determine the factor weight in job evaluation [7] (2010). Experts have also proposed several automatic scheduling algorithm and models. For instance, by defining scheduling template, work positions and other relating elements, Zhu Gang and Du Zhiliang (2013) proposed an automatic scheduling algorithm based on genetic algorithm and applied the algorithm to on-site scheduling [6]; In 2017, Wang Lili and Wang Ning also designed an equity-based scheduling algorithm for controllers [5].

Over the years, large air traffic control units in China have committed to achieve automatic scheduling of controllers. Though many units have developed automatic scheduling software for controllers, due to the large deviation between the manual and automatic generated results, these products were put in limited use. Two of the major difference include:

- While satisfying constraints of each position, automatic scheduling software keeps seeking the optimal solution of the controller working in that position
- For monitoring and commanding positions, automatic generated results generally fail to meet the qualifications in terms of personality complement and ability matching.

2.2 Current Scheduling Problems
For most domestic air traffic control units, controller scheduling works are performed manually by supervisors or specialized staff in Excel or Microsoft Word. The usual scheduling timespan is seven days. Since controllers may ask for leave, attend re-training, business-trip or meeting, a long scheduling timespan becomes unfeasible. Though manual scheduling can satisfy the operational requirements of air traffic control units, it also has the following problems:

- It becomes inconvenient to record operational data, including controller’s duty and vacation time. For supervisory and safety management units, controller’s duty time is a crucial factor to determine whether air traffic control units have enforced the various state regulations regarding controller’s duty and vacation time. The duty time is also an indication for controller’s workload and may provide valuable advices to future policymaking. However, manual scheduling makes it hard to record each controller’s operational data. In fact, it is discovered that some control units do not even save the records of previous controller schedules.
Manual scheduling may fail to satisfy the duty time requirement for controllers. While manual scheduling is done in human brains, when controller amount becomes larger, it becomes hard for the scheduling staff to keep track of each controller’s duty time. Since certain control groups may contain more than forty controllers, some controller’s duty time may exceed the time requirements specified in the regulations on a weekly or monthly basis.

Manual scheduling has poor emergency response capability and adaptability. In real life, when a time off is necessary for a controller, he/she needs to find another controller who is willing to take his/her shift and submit the request to supervisors. However, if the controller couldn’t find someone to take his/her shift, it becomes supervisor’s responsibility to find the right match, who can only solve the puzzle with experience and memory. An automatic scheduling system with emergency response functions can solve the puzzle with computation and decrease the time cost of the whole process.

Therefore, to deal with the above drawbacks, it is necessary to analyze scheduling habits of scheduling staff and develop an automatic scheduling system to meet the operational requirements of air traffic control facilities.

3. Fundamental Scheduling Rules

3.1 Constraints Affecting the Scheduling Activities

In the controller scheduling process, there are multiple factors affecting the scheduling result. The ideal solution is that every controller in the schedule meet the constraints, which is used as the basis for determining scheduling plan. Constraints can be roughly divided into two categories: one is the institutional constraint, which is mandatory; the other is the conditional constraint, which we want to satisfy as many as possible.

For institutional constraints, Civil Aviation Administration of China adopted Air Traffic Management Rules for Civil Aviation (CCAR-93-R5) on May 1st, 2018. It clearly defines the various duty hours of the controller, including the longest continuous duty time for a single shift, the longest continuous duty time in one calendar week, the minimum interval between two duties and continuous break time for each calendar year. This kind of institutional constraints not only conforms to the work plan of each control unit, realize the optimal allocation of human resources, but also meet the fairness requirements.

Conditional constraints can be classified into three subcategories. The first subcategory includes the personal qualifications of the controller. These constraints include suitable duty positions/sectors, qualification certificates, ICAO English level, controlling licenses and night duty availability. The second is the environmental requirements: post/sector complexity, the flight flow within the airspace, and the position qualification requirements. The last subcategory is the staff collocation. These factors include collocation between experienced and new controllers, personality complement for controllers on commanding and monitoring positions, comprehension and skill complement.

3.2 Scheduling Rationales

The scheduling process for controllers is filling in a two-dimensional table (template). Timespans and controlling positions form the coordinate system, as shown in figure 2. Based on fairness and rationality, controllers satisfying various constraints are placed in each grid (module) of the table (template). The constraints include institutional constraints, condition constraints, etc. The process of filling the table is the scheduling method to be discussed.

4. A Machine-Learning Based Scheduling Algorithm for Controllers

4.1 Machine-Learning Based Algorithm

The scheduling problem has been proved by mathematicians to be NP (Non-deterministic Polynomial)-hard problem in the 1970s. Common algorithm for scheduling problems can be classified into two categories. The first one is the optimization algorithm. It obtains the optimal solution from feasible
solution space under known constraints, which requires long computing time and has low efficiency. The second type is the heuristic algorithm, such as genetic algorithm. Heuristic algorithm adopts the evolutionary principle called survival of the fittest and evolves from generation to generation to produce better approximate solutions. However, in practical applications, it is difficult to meet the requirements of multi-objective optimization.

According to the needs of frontline control units, controller scheduling has high complexity, but not many constraints can be quantitatively described. This makes controller scheduling a multi-objective optimization problem. Both optimization and heuristic algorithm become unsuitable. Controller scheduling is a rational sorting process that satisfies both institutional constraints and conditional constraints, while maintaining certain fairness. However, there are certain manual scheduling rules that cannot be articulated as constraints, which are based on the scheduling experience and habit of scheduling staff. To make the automatically generated schedules closer to the historical manual results, we may first apply machine-learning to obtain these subjective rules. Then we combine them with institutional constraints and conditional constraints during the scheduling process.

4.2 Controller Scheduling Algorithm Based on Machine-Learning

Based on the above discussions, to satisfy the actual scheduling requirements of air traffic control units, this paper proposes a machine-learning based controller scheduling method which uses historical data and combines with optimization algorithm. The algorithm uses computing power to learn historical scheduling data, acquire scheduling rules, and simulate manual scheduling. For some modules that cannot be filled by machine learning results, it applies the optimization algorithm to select the most suitable controller for the modules. Main steps include:

- Select scheduling templates according to the requirements of air traffic control units. Due to the difference in personnel, flight flow and airspace etc, control units have distinctive timepoints for shift changing and opening/combing of controlling positions. Therefore, we need to find the appropriate scheduling templates according to the requirements of different air traffic control units. Though scheduling is done on the group level, to reflect fairness, night shift numbers of controllers should be kept balanced. As a result, each controlling group may have several different scheduling templates.
- Fill the most recent matching schedule into the template. According to the manual scheduling habits in frontline control units, new schedules are built from the last scheduling outcomes that matches the group’s situation (such as personnel composition etc). Scheduling personnel then put staff vacation and other absence reasons in consideration to slightly adjust the scheduling outcome.
- Conduct constraint checks for controllers in the modules. Institutional constraints, conditional constraints and fairness of night duty shifts should be put into consideration. For modules which fail to satisfy constraints, or the personnel is no longer available, the algorithm will first mark it as empty. Then it will apply machine learning to select the controller with the highest probability of being on the module in the historical data and populate his/her into the module. If a module has multiple controller choices, pick the one with highest matching probability.
- For empty modules that could not be filled by historical data learning, the algorithm will apply the optimization algorithm to find the most suitable controller, according to constraints such as controlling ability and job qualifications.
- Finally, since scheduling staff may have more awareness on subjective factors including controller’s personality traits and controlling abilities, they may also tune the automatically generated schedule to generate the final scheduling result.

A flow chart of the scheduling algorithm is shown in figure 1 below:
All templates for the controlling group.

Fill the matching template into the scheduling table.

Do all modules satisfy the constraints?

Yes

Name the modules which fail to satisfy constraints as empty.

Conduct machine-learning on historical data and fill the empty modules with appropriate controllers.

Does empty module still exist after machine-learning?

Yes

Does empty module still exist after machine-learning?

Scheduling staff review the automatically generated result.

Does the schedule meet the actual requirements?

Yes

No

Scheduling staff tuned the unsatisfied modules.

Generate the final practical schedule.

Figure 1. Flow chart of the machine-learning based controller scheduling algorithm.

5. Test Description
In order to verify the practicality of the machine learning-based controller scheduling method, an automatic controller scheduling system has been developed based on the algorithm.
Figure 2. One of the excel tables in historical scheduling data

There is usually no uniform standard to evaluate manual scheduling in control units. Some control units are accustomed to scheduling in one week, while others conduct scheduling for each day. However, for the algorithm, scheduling in weeks is a complex version of scheduling in days with more frequent machine-learning and optimization. Therefore, difference in scheduling timespan has limited impact on the verification process. The test verifies the algorithm in days and imports a controlling group’s historical scheduling data as training data. Figure 2 is the screenshot of a recent scheduling table for the group. To analyze the advantages and drawbacks of the machine-learning based algorithm, scheduling results generated by the optimization algorithm are used as comparison. Both algorithms are required to generate the group’s scheduling table on May 26th.

To generate a new scheduling table for May 26th, the automatic scheduling system picks scheduling data on May 20th as template (figure 2) and forms the schedule based on machine-learning results and constraints. The results are displayed in the excel table in figure 3. Meanwhile, the scheduling table automatically generated by the optimization algorithm is shown in figure 4. The actual manual scheduling result on May 26th was collected from the control unit and displayed on figure 5.

Figure 3. Machine-learning based scheduling results
Figure 4. optimization-based scheduling results

| Shift Time     | ACC01/02 command | ACC01/02 monitor | ACC02 command | ACC02 monitor | ACC03 command | ACC03 monitor | ACC04 command | ACC04 monitor | ACC05 command | ACC05 monitor | ACC05 coordinate |
|---------------|-----------------|-----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------|
| 0830-0930     | 2L              | L2F             | CL            | 2M            | HCT           | SY            | SM            | CTX          | JLT           | JTY           | GH             |
| 0930-1130     | LS              | ZL              | LHY           | XL            | JGW           | GY            | MPJ           | ZY            | JY            | HF            | LJ             |
| 1130-1330     | 2L              | L2F             | CL            | 2M            | HCT           | SY            | SM            | CTX          | JLT           | JTY           | SJ             |
| 1330-1530     | LS              | ZL              | LHY           | XL            | JGW           | GY            | MPJ           | ZY            | JY            | HF            | LY             |
| 1530-1730     | 2L              | L2F             | CL            | 2M            | HCT           | SY            | SM            | CTX          | JLT           | JTY           | TH             |
| 1730-1930     | LS              | JW              | LHY           | XL            | JGW           | GY            | MPJ           | ZY            | JY            | HF            | LJ             |
| 1930-2130     | 2L              | L2F             | CL            | 2M            | HCT           | SY            | SM            | CTX          | JLT           | JTY           | JH             |

Figure 5. Manual scheduling result from the scheduling staffs

| Shift Time     | ACC01/02 command | ACC01/02 monitor | ACC02 command | ACC02 monitor | ACC03 command | ACC03 monitor | ACC04 command | ACC04 monitor | ACC05 command | ACC05 monitor | ACC05 coordinate |
|---------------|-----------------|-----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|----------------|
| 0830-0930     | ZS              | WWW             | CL            | ZB            | WYC           | SY            | NH            | CJX           | JLT           | LJ            | XY             |
| 0930-1130     | LS              | ZL              | GY            | XL            | JGW           | SW            | MPJ           | ZY            | LJ            | HF            | LJY            |
| 1130-1330     | SY              | WWW             | CL            | ZB            | WYC           | SY            | NH            | CJX           | JLT           | LJ            | PWH            |
| 1330-1530     | LS              | ZL              | WJ            | XL            | JGW           | GY            | MPJ           | ZY            | LJ            | HF            | LJY            |
| 1530-1730     | ZS              | WWW             | CL            | ZB            | WYC           | SY            | NH            | CJX           | JLT           | LJ            | JH             |
| 1730-1930     | LS              | ZL              | WJ            | PWH           | JGW           | GY            | MPJ           | ZY            | SW            | HF            | LX             |
| 1930-2130     | ZS              | WWW             | CL            | ZB            | LJ            | SY            | NH            | CJX           | JLT           | LJ            | JH             |

While marked modules represent inconsistent results with manual scheduling, the comparison between the tables in figure 3, 4 and figure 5 shows that even though both automatically generated schedules are different from the manual one, the schedule generated by machine-learning based algorithm (figure 3) has less variance (marked modules) compared with optimization-based one (figure 4). Therefore, the machine-learning based schedules have more accordance with manual schedules and become more acceptable to frontline control units. The deviated modules can also be tuned by scheduling staff to achieve consistency with manual scheduling. As a result, adopting automatic scheduling system will not only increase the scheduling efficiency, but also record duty time and rest time of controllers. These statistics may increase the awareness of dominant ATC agencies on working situations and workload of controllers, which can provide data support for formulation of corresponding regulations.
6. Conclusion
With the rapid development of air traffic, working pressure on controllers has increased dramatically. Frontline control units are faced with problems such as limited number of controllers, high pressure, and increased shift work fatigue. Meanwhile, traditional manual scheduling mode becomes time-consuming and labor-intensive. Within the manual scheduling mode, it’s also hard to conduct statistical analysis on controller’s duty time, which may otherwise provide data support for industrial technologies. While learning from the historical data, the machine-learning based scheduling method authorizes scheduling staff to increase and modify the rules, while meeting their scheduling habits. These traits may increase the universality of the system in control units. After verification in control units, it is logical to claim that, controller schedules generated by the machine-learning based system satisfy the scheduling requirements and are in lines with the manual scheduling results, which is significant to the optimal allocation of human resources in air traffic control units.

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